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THESIS

DIFFERENTIAL SOLUTIONS USING LONG-RANGE DUAL-FREQUENCY GPS CORRECTION DATA

by

Fred L. Lindy

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Thesis Advisor:	James R. Clynch
Co-Advisor:	James N. Eagle
Second Reader:	Samuel E. Buttrey

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Military applications of space-based navigation systems have led to important enhancements to our fighting capability and are being applied to many phases of operations. The Global Positioning System (GPS) is a key factor for making this a reality. GPS provides accurate position, velocity and time information. Stand-alone GPS receivers may not provide the requisite accuracy to fulfill mission requirements. This thesis focused on the accuracy and relevance of applying dual-frequency GPS correction data to compute differential GPS (DGPS) solutions. Analysis was performed to assess the viability of using correction data from reference receivers at extended ranges, 2000-3000 km away, to perform after-the-fact positioning by analyzing stand-alone GPS accuracy versus dual-frequency corrected techniques. This could be extended to real-time operations.

The differentially-corrected technique produced more accurate results than stand-alone GPS at all ranges. The stand-alone GPS horizontal root mean square (RMS) accuracy was 5.9 meters while the differentially-corrected RMS accuracy was under 1.5 meters to 2000 kilometers and under 3.0 meters to 3200 kilometers. The process has applicability in determining GPS solutions for long-range military uses. It is possible to use U.S. or Allied GPS assets at long distances from areas of operations to prosecute targets of high interest.

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DIFFERENTIAL SOLUTIONS USING LONG-RANGE DUAL-FREQUENCY GPS CORRECTION DATA

Fred L. Lindy
Lieutenant, United States Navy
B.S., University of Florida, 1995
B.S., Southern Illinois University, 1995

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NAVAL POSTGRADUATE SCHOOL
September 2002

Author:
Fred L. Lindy

Approved by:
James Eagle, Thesis Advisor

James Clynch, Co-Advisor

Samuel Buttrey, Second Reader

James Eagle, Chairman
Operations Research Department

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ABSTRACT

Military applications of space-based navigation systems have led to important enhancements to our fighting capability and are being applied to many phases of operations. The Global Positioning System (GPS) is a key factor for making this a reality. GPS provides accurate position, velocity and time information. Stand-alone GPS receivers may not provide the requisite accuracy to fulfill mission requirements. This thesis focused on the accuracy and relevance of applying dual-frequency GPS correction data to compute differential GPS (DGPS) solutions. Analysis was performed to assess the viability of using correction data from reference receivers at extended ranges, 2000-3000 km away, to perform after-the-fact positioning by analyzing stand-alone GPS accuracy versus dual-frequency corrected techniques. This could be extended to real-time operations.

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EXECUTIVE SUMMARY

Military applications of space-based navigation systems have led to important enhancements to our fighting capability and are being applied to virtually all phases of operations. The Global Positioning System (GPS) is a key technological factor for making this a reality. The system was developed to provide highly accurate position, velocity and time information. The Global Positioning System is a space-based radio-navigation system and determines receiver positions by performing satellite signal time-of-arrival calculations.

The GPS specification for position accuracy is on the order of a few meters. Accuracy refers to the degree of conformance with the actual position and is affected by measurement errors from each satellite and the user receiver-to-satellite geometry. Accuracy could determine whether a military mission succeeds or not; e.g., hitting the target, combat search and rescue, or rendezvous of forces. Stand-alone GPS receivers may not provide the requisite accuracy to fulfill mission requirements.

This thesis focuses on the accuracy and relevance of applying dual-frequency GPS receiver correction data to compute differential GPS (DGPS) solutions. This mimicked the type of GPS receiver used in military applications. Differential GPS is a technique for improving GPS position accuracy. DGPS provides a means by which measurement errors can be cancelled out. The concept is based on the premise that receivers in the same area will experience similar measurement errors.

A data collection experiment was conducted from November 28, 2001 through December 11, 2001 aboard the Research Vessel PT SUR sailing off the coast of Monterey, California. The purpose of the experiment was to the gather data in order to perform long-range, dual-frequency DGPS corrections using data from continuously operating reference station (CORS) sites. The experiment was designed to use multiple receivers 24 hours a day for the duration of the ship's underway time.

The satellite signal contains information regarding its orbit, and the reference receiver is located at a known position. Therefore, the true range to each satellite can be calculated. By comparing the calculated true range with the measured range, a correction

term can be determined for each satellite. The corrections are then broadcast to users in the local area. This data is typically relevant only in the proximity of the reference receiver, up to 300 km, since the same conditions that contributed to the errors are common to both receivers. This thesis explored the viability of using correction data from these receivers at extended ranges, 2000-3000 km away, to perform after-the-fact positioning by analyzing the present stand-alone GPS accuracy versus dual-frequency corrected techniques. This thesis answered the following questions:

- Is it feasible to utilize correction data at these extended ranges?
- What is the GPS accuracy when using correction data at extended ranges from reference receivers?
- What are the limiting factors in the application of these techniques and why?

The question of whether or not it is feasible to utilize correction data at these extended ranges was answered by analyzing the number of satellites in simultaneous view and the dilution of precision. The solution process required a minimum of four satellites in simultaneous view to compute a solution. There was an average of more than seven satellites in simultaneous view for all reference stations at every range. Overall, the percentage of time that the process was unable to compute a solution due to an insufficient number of satellites was less than five percent.

The geometry of the satellites used to perform computations was satisfactory even at long ranges. The ratio of data edits due to poor position dilution of precision (PDOP) increased with range. However, less than 20% of the total data points were edited due to PDOP. It was noted that raising the maximum value for PDOP from six to seven yielded a 30% reduction in the number of edits at 3200 km.

The accuracy for the process was assessed by examining the resultant North, East, Up solution errors. The mean values for the solution errors were sub-meter up to 3200 kilometers and were consistent with a negative bias. However, the standard deviations from the means increased at ranges beyond 2500 kilometers.

The limiting factors of the process were due to the troposphere and multipath effects. The largest bias in the position solution was caused by the troposphere effect. The model used to estimate the troposphere effect induced unpredictable biases into the North position solution. The mean values for the errors shifted between positive and negative values as the range increased. The troposphere model showed a linear increase of the East error with distance.

Further analysis into the variables for the troposphere model revealed that differences in satellite elevation angles caused a greater change in the correction factor than did changes in the weather parameters. Troposphere models should consider the elevation angles relative to the user.

Multipath problems affected the solution process. Excessive multipath errors experienced at some reference stations caused significant degradations in solution accuracy. Satellite measurements were excluded from the solution due to multipath. This often resulted in having an insufficient number of satellites to perform computations. Multipath should be an important factor when selecting reference stations for differential corrections.

The differentially-corrected technique produced more accurate results than stand-alone GPS at all ranges. The stand-alone GPS horizontal root mean square (RMS) accuracy was 5.9 meters while the differentially-corrected RMS accuracy was under 1.5 meters to 2000 kilometers and under 3.0 meters to 3200 kilometers. This process has applicability in determining GPS solutions for long-range military uses, and it may be possible to use U.S. or Allied GPS assets at long distances from areas of operations to prosecute targets of high interest.

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I. INTRODUCTION

A. GENERAL

"Nothing is more difficult than the art of maneuver" - Sun Tzu

Getting from point A to point B can be a challenging endeavor. Once we leave familiar surroundings, ascertaining our position and finding our way can require the use of sophisticated navigation techniques. The tools of navigation evolved from using rudimentary instruments such as sextants and charts to complex, space-based radio navigation systems. Sailors looked to the skies using the sun during the day and stars at night to find their way. Satellites supplanted these celestial bodies and provide more accurate means for determining position.

Military applications of these space-based navigation systems have led to important enhancements to our fighting capability and are being applied to virtually all phases of operations. Weapons platforms can deliver high accuracy precision-guided munitions with the potential to increase target-kill efficiency (FAS, 1997). Warheads the fraction of the size of today's weaponry could perhaps be used to neutralize a target while minimizing collateral damage. A weapons platform could carry a larger arsenal than current configurations allow, thus increasing its combat effectiveness.

The Global Positioning System (GPS) is a key technological factor for making this a reality. The GPS program began in the 1970s to provide an unlimited number of users with navigation data 24 hours a day in all weather conditions. The system was developed to provide highly accurate position, velocity and time information to meet current and future demands for military and civilian users worldwide (ARINC, 1991).

The GPS specification for position accuracy is on the order of a few meters. Accuracy refers to the degree of conformance with the actual position and is affected by measurement errors from each satellite and the user receiver-to-satellite geometry. Accuracy could determine whether a military mission succeeds or not; e.g., hitting the target, combat search and rescue, or rendezvous of forces.

Stand-alone GPS receivers may not provide the requisite accuracy to fulfill mission requirements. Possible solutions for increasing accuracy are either to invest in

new technology by upgrading user equipment, which could be expensive, or to incorporate more robust processing techniques. Differential GPS (DGPS) techniques allow for higher accuracy positioning. Two common techniques for differential GPS are standard DGPS and kinematic DGPS. Standard DGPS performs range position solutions that are accurate to one meter. Kinematic DGPS performs phase corrections and achieves accuracies of 20 centimeters to 4 meters. These methods rely upon reference stations to provide the necessary corrections.

The United States Coast Guard maintains a coastal reference system for mariners using standard DGPS near U.S. territorial waters. National and international networks provide corrections for many places around the world. The correction factors are typically relevant only in the region of the reference station. This thesis proposes using correction data beyond the nominal range of the reference stations and examining the effect on position accuracy.

B. PROBLEM DEFINITION

This thesis focuses on the accuracy and relevance of applying long-range, dual-frequency GPS receiver correction data to compute differential GPS (DGPS) solutions. This mimicked the type of GPS receiver used in military applications. Typically, correction data is assumed valid within 300 kilometers of the reference station. The analysis will ascertain whether the correction data from these receivers at extended ranges, 2000-3000 km away, is useful for performing real-time positioning. This thesis will explore the applicability of using these position solutions for long-range military uses by analyzing present stand-alone GPS accuracy versus dual-frequency DGPS corrected techniques.

The goal is to demonstrate that it is possible to use U.S. or Allied GPS assets at long distances from areas of operations to prosecute targets of high interest. For example, the distance from Bahrain to Iraq is approximately 1000 km, and from Bahrain to Afghanistan is 2000 km. Both are within the range of analysis of this thesis. This thesis addresses the following questions:

- Is it feasible to utilize correction data at these extended ranges?

- What is the GPS accuracy when using correction data at extended ranges from reference receivers?

- What are the limiting factors in the application of these techniques and why?

C. SCOPE

This research incorporates statistical methodology to explore the viability of using long-range, dual frequency correction data. The characteristics of the errors were explored to determine their effect on position calculations. Software tools were developed to format and process data from GPS receivers and analyze the correction data used to generate solutions. The positions were calculated using precise satellite ephemeris data files to provide solutions that are more accurate. Precise ephemeris files are currently provided in real-time by the International GPS Service (IGS, 2002).

D. LITERATURE REVIEW

1. The Concept of Using Long-Range Differential Corrections

Oscar Columbo's article, *Long-Distance Kinematic GPS*, (Columbo, 1998) addressed the importance of being able to calculate precise differential positions using kinematic DGPS up to a few thousand kilometers from the nearest reference station. He described the issues and problems associated with using correction data at great distances. As distance between the reference station and user receiver increases, the measurement errors diverge enough that the effects do not cancel out; therefore the errors must be estimated. Another issue with increasing distance is that the reference receiver may not see the same satellites as the roving receiver.

Some GPS positioning techniques rely on a certain minimum number of satellites being visible. Standard GPS solutions require four satellites to be in simultaneous view to solve for the coordinates and clock error. Kinematic DGPS uses five satellites; four used to compute positions and the receiver clock error, and one to resolve biases. This technique usually requires the roving receiver to be within 700 kilometers of the reference station.

Columbo delved further into the details of the errors and presents issues of concern when processing data. This thesis will try to address the magnitude and scope of

the errors and provide the reader with viable methods for increasing GPS position accuracy at ranges beyond 700 kilometers. Columbo provided an excellent basis for exploring the possibilities of implementing long-range corrections.

2. Accuracy of Long-Range Differential Corrections

The article *Accuracy of GPS-derived Relative Positions as a Function of Inter-Station Distance and Observing-Session Duration,* written by M. W. Cline, M. C. Eckl, G. L. Mader, R. A. Snay and T. Soler, (Cline, 2001) explored how the accuracy of the position solution varied based upon the distance from the reference receiver and the duration of the observing session. The authors processed ten days of data focusing on distances between 26 and 300 kilometers from 4 to 24 hours in length. The selection of the distance and time interval coincides with typical conditions for standard DGPS users who rely upon the National CORS (Continuously Operating Reference Stations) system for correction data.

The authors concluded that the distance had little impact on the corrected solution once precise satellite, vice broadcast, orbits were used. They derived equations to capture the magnitude of the standard error, in north-east-up dimensions, which were based upon time. Other factors, such as the methodology and software used, also affected the accuracy of the experiment. This thesis will examine any affects caused by inter-station distances of up to 3200 kilometers.

3. Potential Military Applications of using Differential Corrections

Lawrence L. Wells, author of *The Projectile GRAM SAASM for ERGM and Excalibur,* (Wells, 2000) outlined the Army and Navy plans to develop guided munitions that incorporate GPS aligned inertial measurement units (IMU) to perform in-flight guidance. The Army's project, Excalibur, is designed for use with 155 mm platforms. The Navy's project, Extended Range Guided Munitions (ERGM), is used with 5" deck guns. The projectiles incorporate GPS receivers that must be able to quickly and accurately determine their position in a battlefield environment. This capability offers a relatively low-cost "smart" weapon and is a potential application for utilizing the results of this thesis.

4. Availability of GPS Correction Data

Chop, J., Judy, C., Kritz, A., Wolfe, D., in their article *Local Corrections, Disparate Uses Cooperation Spawns National Differential GPS*, described the U.S. Department of Transportation's (DOT) initiative to expand differential GPS (DGPS) to provide coverage within the continental United States. The National Differential GPS network (NDGS) shares data with the continuously operating reference station network. Approximately 80% of the U.S. receives coverage with growth projected to encompass all areas in two years. The International GPS Service (IGS) provides GPS data in near real-time to users covering some areas around the world. The concept of network-linked differential corrections is expanding to provide truly global coverage. This thesis utilizes data that is available from networks. Data availability and applicability will be enhanced as these networks expand.

E. THESIS OUTLINE

General details about the Global Positioning System are contained in Chapter II. An explanation and characteristics of the components that comprise GPS and fundamental concepts of operation are included to impart the reader with requisite background information. Next, Chapter III describes the data collection experiment. Chapter IV provides the main thrust of the thesis by detailing the analysis performed on the data collected. This segues into the conclusion and recommendations for future research in Chapter V.

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II. BACKGROUND

A. GPS BASICS

Eliot Kaplan, *Understanding GPS: Principles and Applications,* (Kaplan, 1996) provided most of the information contained in this chapter, although many similar references exist.

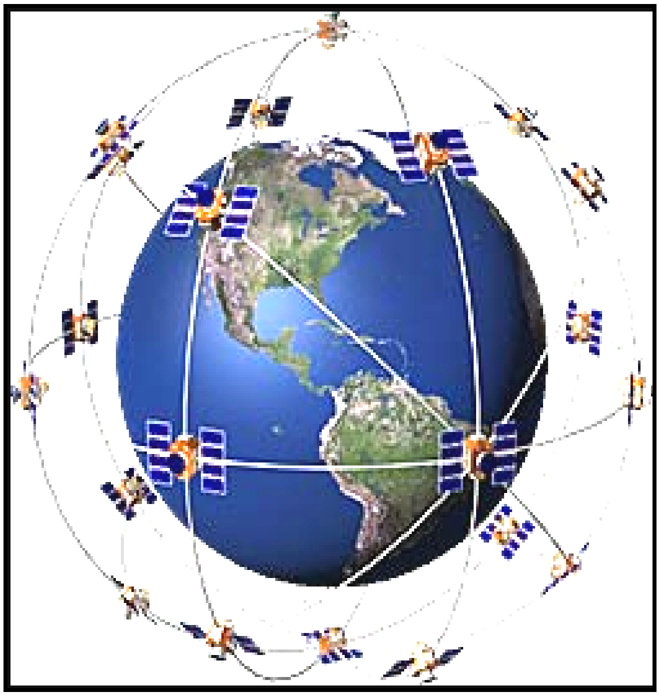

Figure 1. GPS Satellite Constellation (From: Garmin, 2002)

The Global Positioning System is a space-based radio-navigation system used to measure position, velocity and time. The system relies on satellite signal time-of-arrival calculations. Satellites simultaneously broadcast on two separate frequencies ranging codes, which identify the satellite by number and signal transmission time, and navigation data. The ranging codes are integral for determining the satellite-to-receiver range. The navigation data provides the satellite's location at the time of transmission. Receiver position determination will be discussed in further detail later.

The signal transmission time is based upon onboard, high-accuracy atomic clocks synchronized with Coordinated Universal Time (UTC), and managed by the United

States Naval Observatory (USNO). The offset of the satellite's time from UTC is monitored and adjusted to ensure that clock errors are less than 100 nanoseconds.

GPS is a dual-use system developed by the Department of Defense that is designed to support both military and civilian users. It provides two main services. The Precise Positioning Service (PPS) offers highly accurate positioning data with a design specification accuracy of approximately 15 meters. PPS is intended primarily for military users. The Standard Positioning Service (SPS) was intended to provide civilian users with GPS capability, but with less accuracy than PPS. It is designed for a minimum accuracy of 100 meters (USNO, 2001). The difference between the specified accuracy of PPS and SPS was due to the intentional degradation of the satellite signal through the technique known as Selective Availability (SA). This was done in order to provide GPS benefits to the greatest number of users while preserving the national security interests of the United States. The President of the United States discontinued the use of SA on May 1, 2000 (Asst. SECDEF, 2001).

These services provide sufficient accuracy for most navigation applications. Accuracy of a position at a given time refers to the degree of conformance of that position with the true position at that time. However, more robust processing techniques are capable of achieving sub-meter accuracy. Post-processing applications may incorporate corrections from reference stations and/or use two-frequency carrier phase observations to further increase position accuracy (Kaplan, 1996). The technique of utilizing differential corrections achieves higher accuracy and forms the basis for GPS position enhancements in this thesis.

1. GPS Segments

The GPS system comprises three main segments: the space segment, the control segment, and the user segment. The space segment consists of at least 31 satellites in six orbital planes separated by 60° and at a 55° inclination angle to the equatorial plane. This orbit causes satellites moving in opposite directions to intersect at a nearly 90° angle which provides better geometry for position determination. The orbit period is 11 hour 58 minutes, which is half of a sidereal day, and its radius is approximately 26,600 km (Kaplan, 1996). The same satellite will be over the same position on the ground four

minutes earlier each calendar day. This orbital design was chosen to ensure that at least four satellites are always visible 24 hours a day from any location.

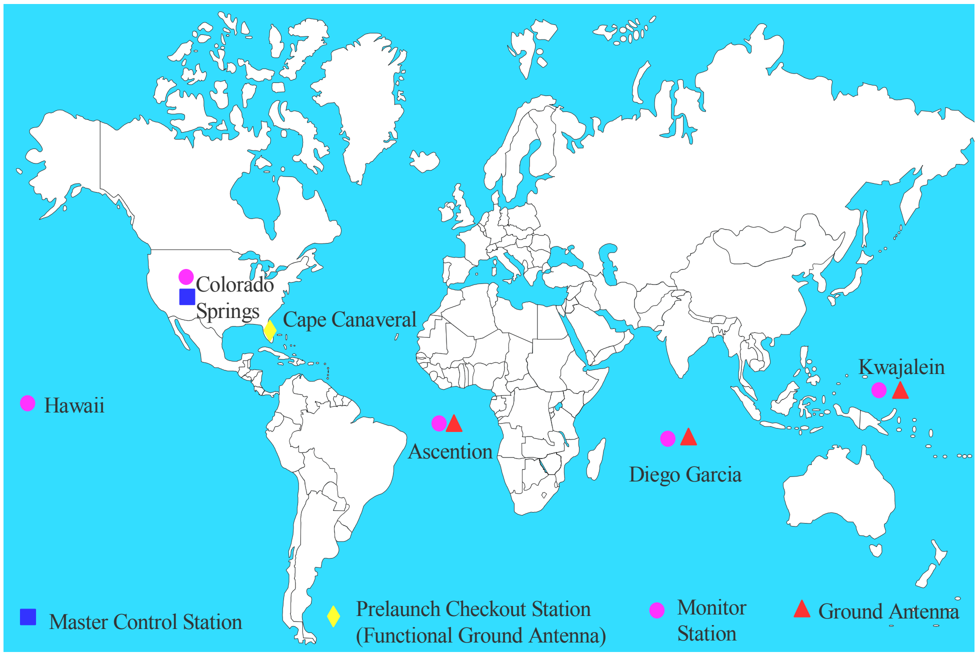

Figure 2. World Map of GPS Control Segment Elements (From: USCG, 1999)

The control segment consists of a master control station, five monitoring stations and three ground antennas. The control segment is responsible for maintaining the satellites in their proper orbit, monitoring system health, updating onboard clocks and uploading data for the navigation message. The master control station (MCS) is located at Schriever Air Force Base, Colorado. The MCS receives data from the monitoring stations and determines the corrections, satellite orbit ephemeris and almanac data for each satellite (USNO, 2001). The MCS also assesses the health of the satellite constellation and monitors station status.

The monitoring stations are located at Colorado Springs, Hawaii, Kwajalein, Ascension Island, and Diego Garcia. These stations track the satellites in view and perform range measurements using both GPS signals. This allows for the determination of the errors associated with the ionospheric delay of the satellite signals. Each station records satellite navigation messages and local weather information and forwards this data to the MCS (Kaplan, 1996).

The three ground antennas are co-located with monitoring stations at Kwajalein, Ascension Island, and Diego Garcia. These locations were chosen to maximize satellite coverage. The MCS performs satellite command and control, telemetry and tracking data and message uplinks via the ground antennas. Ground antennas store data until the required satellite is in view of the antenna.

The user segment consists of receivers and antennas that process the signals, which are transmitted in the L frequency band, to determine user position, velocity and time. There are two basic types of receivers: those that receive only the coarse/acquisition (C/A) codes and those that receive both the C/A and precision codes (P/Y). Variations of these receivers allow for measuring the carrier phase of the satellite signal resulting in sub-meter accuracy levels. Most receivers have multiple channels that allow an individual channel to track a single satellite. The ability to track more satellites simultaneously, reduces the circular error probable (CEP) of the calculated position. CEP is the radius of a circle within which 50% of the calculated positions will fall (Dana, 1999).

The capabilities of GPS receivers affect their size and cost. This may become a limiting factor when choosing the proper receiver for the intended mission. Ideally, existing equipment could achieve optimal performance by incorporating more sophisticated processing techniques thus eliminating the need to invest in newer receivers.

2. GPS Signals

All satellites transmit on the same two frequencies, but each is assigned its own unique pseudorandom noise code (PRN) sequences. The PRNs are modulated using a digital spread spectrum technique called code division multiple access (CDMA). The GPS receiver must replicate the PRN sequence in order to extract the information contained in the signals. PRN codes allow the receiver to differentiate one satellite from another. The modulation scheme minimizes signal interference by separating each code sequence.

GPS satellites continuously transmit right-hand, circularly-polarized (RHCP) coded signals on two different L-band frequencies. The signals contain ranging codes

and system data necessary to compute position solutions. The L1 frequency is transmitted at 1575 MHz with a wavelength of 20 centimeters. L1 carries the navigation message and the SPS code signals. The L2 frequency is transmitted at 1227 MHz with a wavelength of 25 centimeters. L2 supports two-frequency corrections, which are used to compensate for the effects caused by ionospheric delay. The satellite transmits these signals at a power level based on a receiver tracking with a 3 dB linearly polarized antenna achieving a minimum signal power level of -160 dBW at the Earth's surface (Asst. SECDEF, 2001).

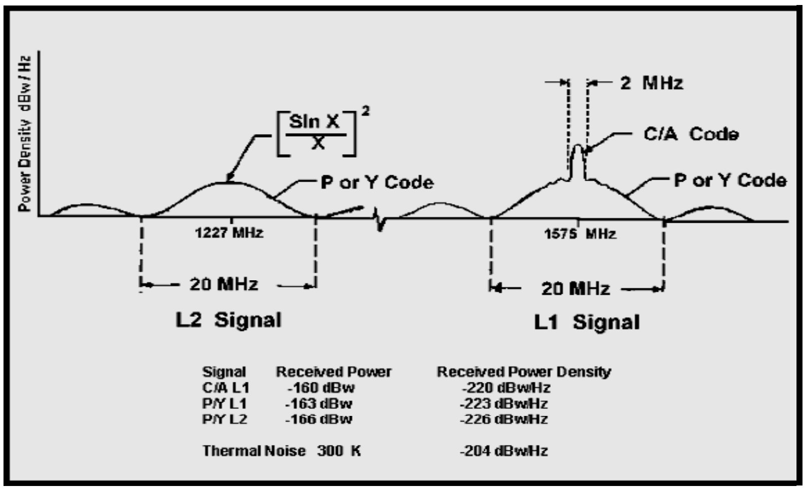

Figure 3. L1 and L2 Signal Characteristics (From: NAVSTAR GPS JPO, 1996)

The P/Y code is primarily for military use and is a 10 MHz bit-rate signal that modulates both L band frequencies. The code contains a set of 37 mutually exclusive PRN codes and has a length of seven days. Initialization of the code occurs at 0000 hours each Sunday establishing the start of the GPS week. The Y-code is an encrypted version of the P-code and is used when the GPS system is in the anti-spoofing (A-S) mode. Anti-Spoofing denies unauthorized access to the Y-code and helps prevent receivers from locking onto mimicked GPS signals, which might provide incorrect positioning information. The P/Y code forms the basis for the PPS. The C/A code modulates L1 and provides the mechanism to identify each satellite in the constellation. The code sequence repeats each millisecond and forms the basis for SPS (Asst. SECDEF, 2001).

Each satellite broadcasts a navigation message based upon data periodically updated by the master control station and adds it to the C/A code. The navigation

message is a 50 Hz signal that describes the satellite orbits, clock corrections, and other system parameters. The message consists of time-tagged data for the transmission of each frame transmitted by the satellite. A data frame is transmitted every thirty seconds and three six-second subframes contain orbital and clock data. Satellite clock corrections are sent in subframe one and ephemeris data is sent in subframes two and three. The complete navigation message requires 12.5 minutes to transmit (Kaplan, 1996).

3. Satellite Orbit Data

One of most important elements of data for computing accurate GPS solutions is the true position of the satellite. Ephemeris parameters describe the coordinates of the satellites for small segments of their orbits. Receivers incorporate new ephemeris data hourly, but the data is valid for up to four hours without too much deviation. Broadcast ephemeris sets are changed by the control segment every two hours and are considered valid for two hours before and after the time of ephemeris (Bisnath, 2000).

Almanacs contain approximate orbit data parameters for all satellites over extended periods. This data is used to preset the receiver with the approximate position of each satellite in the constellation significantly reducing signal acquisition time on receiver start-up. An almanac can be obtained from any GPS satellite. Many receivers update the almanac periodically and store the most recent almanac and the receiver's position in protected memory.

Discrepancies between the ephemeris position and the true satellite position develop over time. These perturbations are attributed to gravitational effects of the earth and sun, magnetic forces, atmospheric drag, solar radiation effects and the earth's non-spherical shape and uneven mass distribution (Kaplan, 1996). Satellite position affects the GPS solution by providing the starting point for range measurements. The next section describes errors caused by inaccurate satellite positions.

Precise ephemeris data refines the accuracy of derived GPS solutions by providing a much better estimate of the satellite's true position. Precise ephemeris data is obtained by utilizing a network of tracking stations and orbit processing facilities to collect and analyze satellite orbit data. This data is post-processed to model the satellite's trajectory at any moment in time.

4. Errors

GPS errors result from a combination of various factors and create a disparity between the true position and the calculated position. Pseudo-range refers to the measured distance determined by the signal propagation time from the satellite to the receiver. The propagation time is based on the satellite-user range plus the errors that delay the transmitted signal.

Errors can be grouped into the following classes:

- Clock Errors (Receiver and Satellite)
- Propagation Errors
- Multipath Errors
- Receiver Errors
- Orbit Errors

Figure 4 displays the relative time-delay contributions of various factors to the time-of-arrival measurement. The range refers to the physical distance between the satellite and receiver. Errors affect the time-of-arrival measurements by delaying the signal and form the crux of the pseudo-range calculation problem.

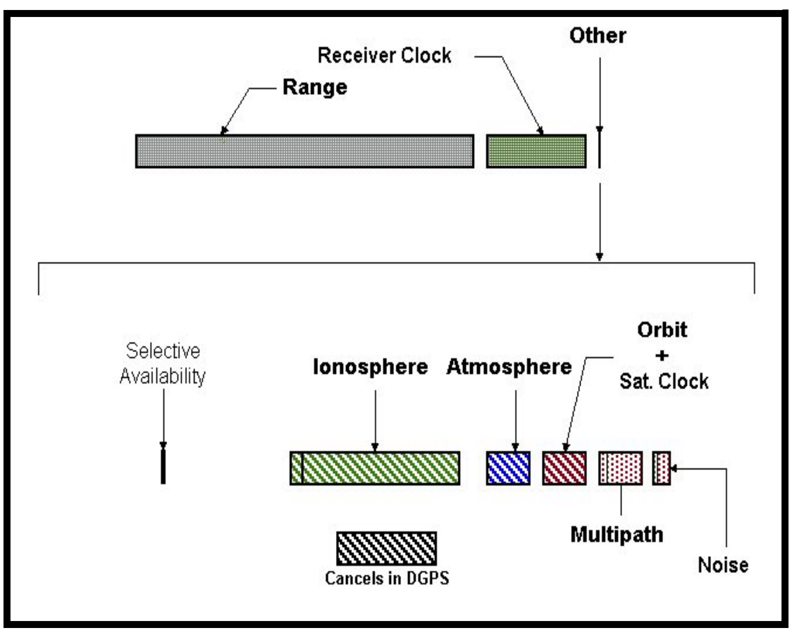

Figure 4. Components of GPS Errors (From: Clynch, 2001)

Clock errors result from the drift of satellite and receiver clocks from UTC. Differences between UTC, satellite and receiver times affect the accurate determination of the true geometric distance between satellites and receivers. The receiver clock is not synchronized with the satellite's onboard clock; thus, a bias is introduced into the pseudo-range measurement. The amount of receiver clock bias is determined while performing range calculations with at least four satellites in view. The navigation message contains information regarding satellite clock bias.

Another source of bias is the delay of the satellite signals as they propagate from the satellite to the user receiver caused by the medium in which the signal travels. The region of the atmosphere ranging from 80 to 1000 kilometers above the earth's surface is known as the ionosphere. Solar radiation ionizes gas creating free electrons which delay satellite signals as they propagate through this region. The magnitude of the delay depends on the refractive index of the ionosphere and the elevation angle of the satellite. The refractive index is based on the electron density and is proportional to the inverse of square of the carrier frequency. Since the ionospheric delay is frequency-dependent, dual-frequency GPS receivers can measure the signal arrival time on both frequencies and algebraically solve for the delay. The navigation message transmits a model to estimate the delay, but the accuracy is subject to fluctuations in the ionosphere (Fonda, 2001).

The troposphere accounts for other propagation delays. The troposphere extends up to an altitude of approximately 80 kilometers. The bias is proportional to the length of path and density of the troposphere. Variations in temperature, pressure and humidity affect the density of the medium in which the signal travels.

Tropospheric effects can be measured at reference stations and the range corrections transmitted to local users. However, satellite geometry, water vapor content and pressure may be different along the propagation paths causing different tropospheric delays to be experienced at other receiver locations. Altitude changes are examined in this thesis, since height affects pressure and the amount of troposphere that the signal transits.

Multipath is the error induced by the reflection of signals from the earth and other objects causing interference of signals reaching the receiver by two or more different paths (Wormley, 2002). Reflected signals travel longer paths resulting in time delays also, the ranging codes are distorted which may cause the receiver to lose synchronization with that satellite signal. Longer signal paths cause pseudo-range measurements to be longer.

To minimize the effects of multipath interference, GPS signals are right-hand circularly polarized; reflected signals are reversed to left-hand circular polarization. Multipath is prevalent at low elevation angles so GPS users can set receivers to ignore signals near the horizon. In addition, placing the antenna above or away from reflective objects minimizes multipath effects.

Receiver errors result from noise and hardware/software anomalies. The magnitude of the error dependent upon each receiver's design. These errors include signal processing, clock/signal synchronization and correlation methods, receiver resolution, signal noise, and others.

Satellite positions obtained from the broadcast ephemeris data contained in navigation message are predictions of where the satellite should be at a given moment, but its actual position is slightly different. The accuracy of the computed position depends on the accuracy of the satellite position since this is the point of reference for measurement equations.

5. Position Determination

The premise for determining GPS positions is based on measuring the distance between the receiver and satellites. This range is determined by multiplying the speed of light by the propagation time while accounting for adjustments and errors. This concept is known as time-of-arrival ranging.

The intersection of four or more satellite range spheres allows for three-dimensional positioning and receiver clock bias determination. Each sphere's center is determined by the satellite ephemeris data and the radius is derived from the signal propagation time (Dana, 1999).

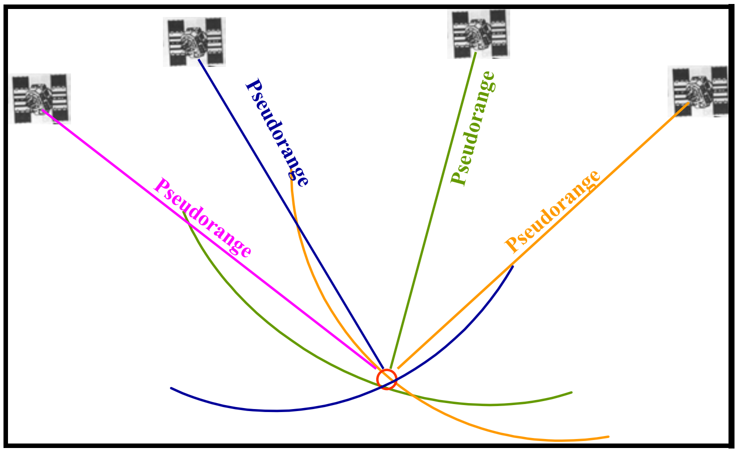

Figure 5. Position Determination from the Intersection of Satellite Range Vectors (From: USCG, 1999)

In practice, GPS determines range by performing pseudo-range measurements to satellites. The concept of pseudo-range is the process by which the user receiver measures the approximate distance between itself and the satellite by correlating the satellite ranging code with the receiver-generated reference code. The signal transmission time reflects the range and is determined by the offset between the signals.

Figure 6 provides the mathematical relationship for the pseudo-range, ρ. The components of the satellite and ground-user position vectors are expressed in Cartesian (x, y, z) Earth-Centered Earth-Fixed (ECEF) coordinates.

Measurement Equation

$$\rho = |\vec{x}_s - \vec{x}_g| + c(\tau_s - \tau_g) + \varepsilon$$

$\vec{x}_s = \mathit{Satellite\ Position}$

$\vec{x}_g = \mathit{Ground, UserPosition}$

$\tau_s = \mathit{Satellite\ Clock\ Error}$

$\tau_g = \mathit{Ground\ User\ Clock\ Error}$

$\varepsilon = \mathit{Errors}$

Set $\ell = c\tau_g$ to make all unknowns lengths

Nonlinear

$$|\vec{x}_s - \vec{x}_g| = \sqrt{(x_s - x_g)^2 + (y_s - y_g)^2 + (z_s - z_g)^2}$$

In Navigation Applications, take $\tau_s = 0$

Figure 6. Pseudo-range Measurement Equation (From: Clynch, 2001)

Several factors from the previous equation are unknown. Initially, the user position is only an estimate and the error terms are unknown. To approximate the GPS solution, the least mean squares method may be used.

The following description introduces the conceptual process for a single time line. This methodology was incorporated in this thesis, however Kalman filtering is used in practice. The process begins with an initial guess of user position, $\vec{x}_{now}$, (x, y, z) and is repeated until stopping conditions are met (Kaplan, 1996). A residual, r_i, is the difference between theoretic ranges, p_i, and measured ranges, $p_{i,m}$, where i is a subscript for the i^{th} observation and m is for the measurement.

The goal is to choose an approximate (x,y,z) position for the user's position, $\vec{x}_{now}$, that is close to the user's true position to minimize the sum of squares of the residuals, $\sum r_i^{\,2}$.

$$r_i = p_{i,m} - p_i$$

$$p_i = \left|\vec{x}_i - \vec{x}\right| = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2}$$

A Taylor series approximation is used.

$$p_i \approx p_i(\vec{x}_{now}) + \frac{\partial p_i}{\partial x}\delta x + \frac{\partial p_i}{\partial y}\delta y + \frac{\partial p_i}{\partial z}\delta z + \ldots$$

The partial derivatives form the components of the unit vector, $\hat{e}_i$, from the user to the satellite.

$$\frac{\partial p_i}{\partial x} = -\frac{(x_i - x)}{p_i}; \frac{\partial p_i}{\partial y} = -\frac{(y_i - y)}{p_i}; \frac{\partial p_i}{\partial z} = -\frac{(z_i - z)}{p_i}$$

And,

$$\hat{e}_i = -\left[\frac{\partial p_i}{\partial x}, \frac{\partial p_i}{\partial y}, \frac{\partial p_i}{\partial z}\right] = -(e_{i,x}, e_{i,y}, e_{i,z})$$

Unit vectors are combined into matrix form, called the H matrix. At least four satellites are necessary to solve for the three-dimensional position and the receiver clock bias. The column of ones is necessary for receiver clock bias determination.

$$H = \begin{bmatrix} -\hat{e}_1, & 1 \\ -\hat{e}_2, & 1 \\ -\hat{e}_3, & 1 \\ -\hat{e}_4, & 1 \\ . & . \\ . & . \\ . & . \\ -\hat{e}_n, & 1 \end{bmatrix} = \begin{bmatrix} -e_{1x} & -e_{1y} & -e_{1z} & 1 \\ -e_{2x} & -e_{2y} & -e_{2z} & 1 \\ -e_{3x} & -e_{3y} & -e_{3z} & 1 \\ -e_{4x} & -e_{4y} & -e_{4z} & 1 \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ -e_{nx} & -e_{ny} & -e_{nz} & 1 \end{bmatrix}$$

The least squares solution update to the estimated user position is determined as:

$$\delta\vec{x} = \begin{bmatrix} \delta x \\ \delta y \\ \delta z \\ \tau_{rcvr} \end{bmatrix} = \left(H^T H\right)^{-1} H^T r$$

The new position, $\vec{x}_{new}$, is derived by incorporating the above update into the old position. The process is repeated starting with the user position being $\vec{x}_{new}$ until stopping conditions are met.

$$\vec{x}_{new} = \vec{x}_{now} - \delta\vec{x}$$

Common stopping conditions include minimum magnitude of change, $\delta\vec{x}$, solution divergence and number of iterations.

The elements of the matrix formed by computing $\left(H^T H\right)^{-1}$ correlate to the covariance matrix of $\delta\vec{x}$ and are integral for determining the dilution of precision, discussed in detail in Section 8.

6. Kalman Filtering

Kalman filtering is a linear, recursive least squares technique for estimating the state of a dynamical system from a sequence of measurements. It is a prediction and update method. Whenever a valid measurement is available, the Kalman update will use it to calculate a more accurate state vector.

In GPS receivers, Kalman filters provide an estimate of user position by recursively comparing range measurements with residuals, which are the differences between the anticipated pseudo-ranges and delta pseudo-ranges, and weighting these values for the next iteration. The weights are adjusted to minimize the impact of residuals with higher values. This scheme assigns a higher weight to more accurate measurements. The process relies on an initial approximate estimation of position, velocity, and time, which may come from the receiver's internal memory of the last known position (Kaplan, 1996).

7. Kinematics

Kinematics is a process used to derive extremely accurate positions of mobile receivers relative to a stationary receiver when both receivers track the same satellites. The positioning process uses carrier phase measurements. The errors in range measurements to satellites common to both receivers are cancelled out.

The process requires both receivers to identify and lock onto each satellite in view. The receivers measure the phase angle and keep a running integer count of the number of frequency cycles. Distance from the satellite to the receiver is proportional to the number of cycles multiplied by wavelength. The integer number of cycles between the satellite and receiver when the receiver initially locks onto the signal is unknown thus creating an integer ambiguity. Integer ambiguity is reduced by systematically estimating an initial position then creating a region of uncertainty, establishing the criteria for selecting potential viable integer values and finally by testing those values until only one solution remains (Hofmann-Wellenhof, 2001).

8. Accuracy

Two important factors are used to measure the accuracy of the position solution: the User Equivalent Range Error (UERE) and Geometric Dilution of Precision (GDOP) (Kaplan, 1996).

The error in the GPS solution can be estimated by

$$\text{Solution Error} = \text{UERE x GDOP}$$

UERE is a measure of the average error in the range measurement to each satellite and varies with time due to perturbations in the satellite signal, signal propagation characteristics, and receiver calculation processes. UERE differs with each satellite at each time increment, but is usually minimal once a new navigation message is uploaded.

GDOP is a dimensionless factor that describes the positional accuracy caused by the geometric relationship of the satellites as seen by the receiver. It is a common figure-of-merit for describing the accuracy of the solution. GDOP varies with satellite motion and receiver location because the geometric relationships continuously change. The positional error is highest when the lines-of-sight between the receiver and two or more satellites approach parallel, or when all four satellites approach the same plane (NAVSTAR GPS JPO, 1996). Figure 7 illustrates the relative positional uncertainty caused by poor satellite geometry. The shaded area is largest when the angular separation between the satellites is small.

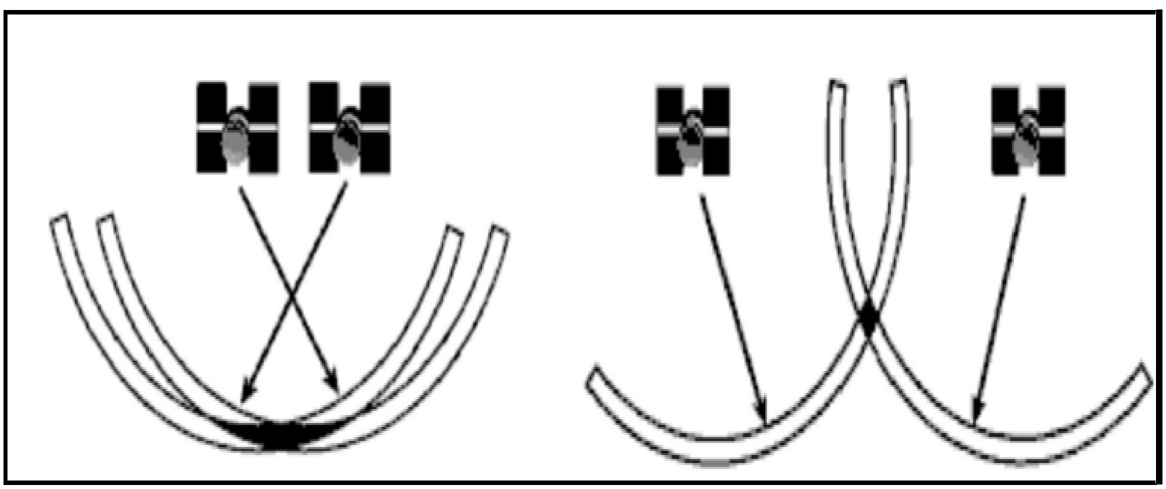

Figure 7. Examples of Satellite Geometry (From: NAVSTAR GPS JPO, 1996)

Other dilutions of precision quantities characterize the accuracy of the derived solution. Position dilution of precision (PDOP) refers to the geometry associated with the three-dimensional position. Horizontal dilution of precision (HDOP) refers to the geometry of the two-dimensional position. Vertical dilution of precision (VDOP) refers

to the height component. Time dilution of precision (TDOP) describes the time bias. Using $\left(H^T H\right)^{-1}$, it is possible to derive the dilution of precision when using the East, North, Up reference system (Kaplan, 1996).

$$\left(H^T H\right)^{-1} = \begin{bmatrix} D_{11} & D_{12} & D_{13} & D_{14} \\ D_{21} & D_{22} & D_{23} & D_{24} \\ D_{31} & D_{32} & D_{33} & D_{34} \\ D_{41} & D_{42} & D_{43} & D_{44} \end{bmatrix}$$

$$GDOP = \sqrt{D_{11} + D_{22} + D_{33} + D_{44}}$$
$$PDOP = \sqrt{D_{11} + D_{22} + D_{33}}$$
$$HDOP = \sqrt{D_{11} + D_{22}}$$
$$GDOP = \sqrt{D_{33}}$$
$$TDOP = \sqrt{D_{44}}$$

9. Coordinate Systems

The Earth Centered, Earth Fixed (ECEF) Cartesian coordinate system is useful for computing GPS position since this coordinate system rotates with the Earth. The components of this system are (x,y,z). GPS receivers perform computations using ECEF coordinates and then convert the position to geodetic coordinates (latitude, longitude, ellipsoid height).

10. Datum

Datum establishes the reference frames used for mapping coordinates and defines the shape of the earth and the orientation of coordinate systems. When performing differential corrections, it is important use the same datum otherwise, position offsets occur. This thesis used the North American Datum of 1983 (NAD 83) as the reference frame to derive GPS positions.

B. DIFFERENCING TECHNIQUES

Differential GPS (DGPS) is a technique for improving GPS position accuracy. DGPS provides a means by which measurement errors can be cancelled out. The concept is based on the premise that receivers in the same area will experience similar measurement errors. The satellite signal contains information regarding its orbit, and the

reference receiver is located at a known position. Therefore, the true range to each satellite can be calculated. By comparing the calculated true range with the measured pseudo-range, a correction term can be determined for each satellite. The corrections are then broadcast to users in the local area. This data is typically relevant only in the proximity of the reference receiver since the same conditions, which contributed to the errors, are common. Near real-time position calculations using this correction technique may achieve centimeter accuracy and thus attain improved telemetry navigation for ships, aircraft or weapon systems.

The following picture shows both a reference station and user receiver performing pseudo-range measurements to satellites in simultaneous view. Since the two receivers are in the proximity of each other, the same phenomena affect both receivers. The reference station computes the residual of measurements to apply to the user's pseudo-range measurements to calculate its position.

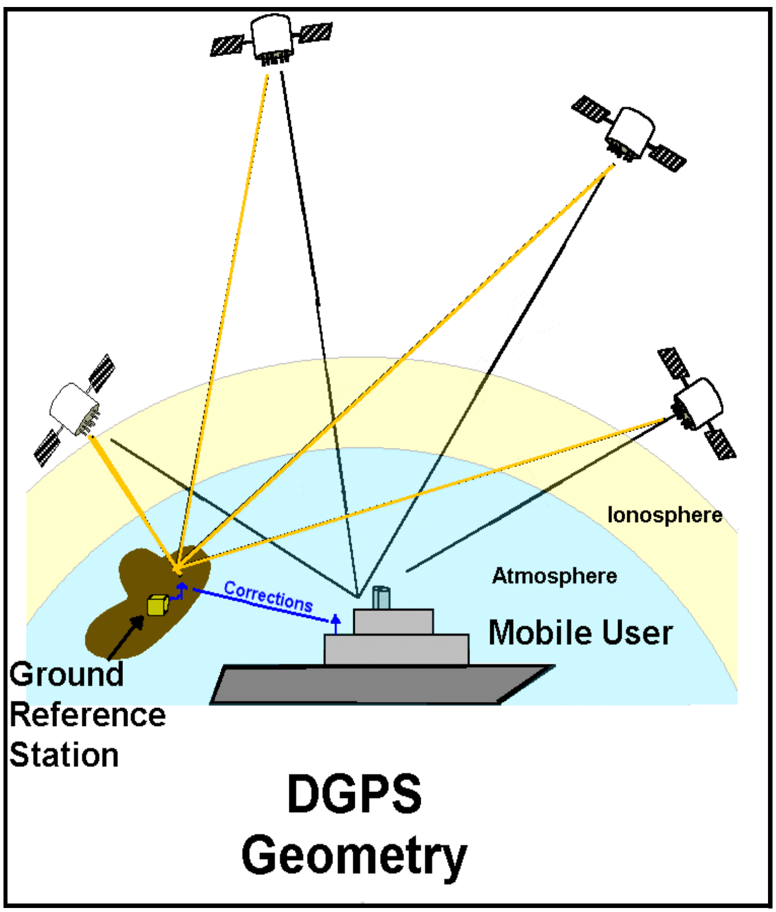

Figure 8. DGPS Conceptual Process (From: Clynch, 2001)

1. Measurement Domain and Solution Domain

Corrections could be applied to either pseudo-range measurements or computed positions. However, practical implementations of DGPS only utilize pseudo-range measurement corrections. Applying corrections to the pseudo-range measurements occurs in the measurement domain. Reference stations compute measurement errors to each satellite in view and determine pseudo-range corrections. The user receiver computes its solution by applying those corrections to range measurements only for the satellites that it views.

If we were to incorporate corrections to GPS positions then inaccuracies could occur. Solution errors result from the combination of the pseudo-range measurements used to compute the solution. Receivers must use the exact same satellites to compute their solutions otherwise, the position error corrections may not be relevant.

C. DATA FORMAT

The data processed in this thesis followed the Receiver Independent Exchange (RINEX) version 2.10 format (Werner, 2001). The format provided consistent fields of reference for the data collected. Many GPS processing software applications use the following data:

- Carrier-phase measurement of one or both carriers
- Pseudo-range measurement
    - The pseudo-range is the distance from the receiver antenna to the satellite including receiver and satellite clock offsets and other biases, such as atmospheric delays.
- Observation time
    - The time of the measurement is the receiver time of the received signals expressed in GPS time.

The most commonly used RINEX file types are the observation and navigation files. The observation file provides carrier-phase measurements, pseudo-range measurements, and observation times. The navigation message file supplies the broadcast ephemeris data for the observed satellites. This thesis used only the observation data files

to provide correction information for the data analysis. The ephemeris data came from precise ephemeris data files and not the navigation message.

D. REFERENCE STATIONS

The National Geodetic Survey (NGS), an office of the NOAA's National Ocean Service, coordinates the network of CORS sites to provide range measurement data to users in the United States. The data is available, via the Internet, to the public for post-processing applications. A complete listing of CORS sites, current as of June 2002, is contained in Appendix A.

Eight sites were chosen as reference stations for this thesis. Site locations differed in distance from the ship, latitude and longitude. Distances between the reference stations and the ship ranged from 100 to 3200 kilometers to observe the inter-station range effects. Site latitudes varied from 27N to 47N and longitudes from 88W to 122W to analyze any potential North-South or East-West affects.

III. DATA COLLECTION EXPERIMENT

A. PURPOSE

A data collection experiment was conducted from November 28, 2001 through December 11, 2001 aboard the Research Vessel PT SUR sailing off the coast of Monterey, California. The purpose of the experiment was to gather data in order to perform long-range, dual-frequency DGPS corrections using data from continuously operating reference station (CORS) sites. The experiment was designed to use multiple receivers 24 hours a day for the duration of the ship's underway time.

B. METHODOLOGY

As the ship transited its planned course, data was collected from high quality Ashtech Z12, dual-frequency GPS receivers aboard the ship and on shore. The data collection on shore occurred at the Naval Postgraduate School and provided control for subsequent data processing. Post-processing the data after the completion of the experiment produced the truth trajectory, the ship's actual track transited during the cruise. A kinematic solution was used to achieve a sub-meter accuracy solution.

Appendix B contains plots of the ship tracks for the days chosen for analysis. The selected days provided various conditions under which to test the fidelity of the correction process. The ship performed open-ocean transits for the majority of the experiment. The transits provided an opportunity to assess the affects of changing latitudes and longitudes on differentially-corrected position solutions. Rough weather forced the PT SUR to take shelter in San Francisco Bay for a few days. During this period, the ship performed oceanographic measurements in the channel leading into the bay. The data collected on these days was subjected to potential multipath errors due to the ship's constant proximity to the Golden Gate Bridge.

Reference station data was obtained from the National Geodetic Survey (NGS) Continuously Operating Reference Station (CORS) network which provides GPS carrier phase and code range measurements in support of 3-dimensional positioning activities throughout the United States (NGS, 2002). CORS data is posted daily on the Internet from which the user may download RINEX (Werner, 2001) data files. The website is

http://www.ngs.noaa.gov/CORS/Data.html. The sites varied in latitude and longitude ranging in distances from 100-3200 kilometers away from Monterey, California. The furthest sites lie on approximately the same longitude to allow for the exploration of effects caused by changes in latitude.

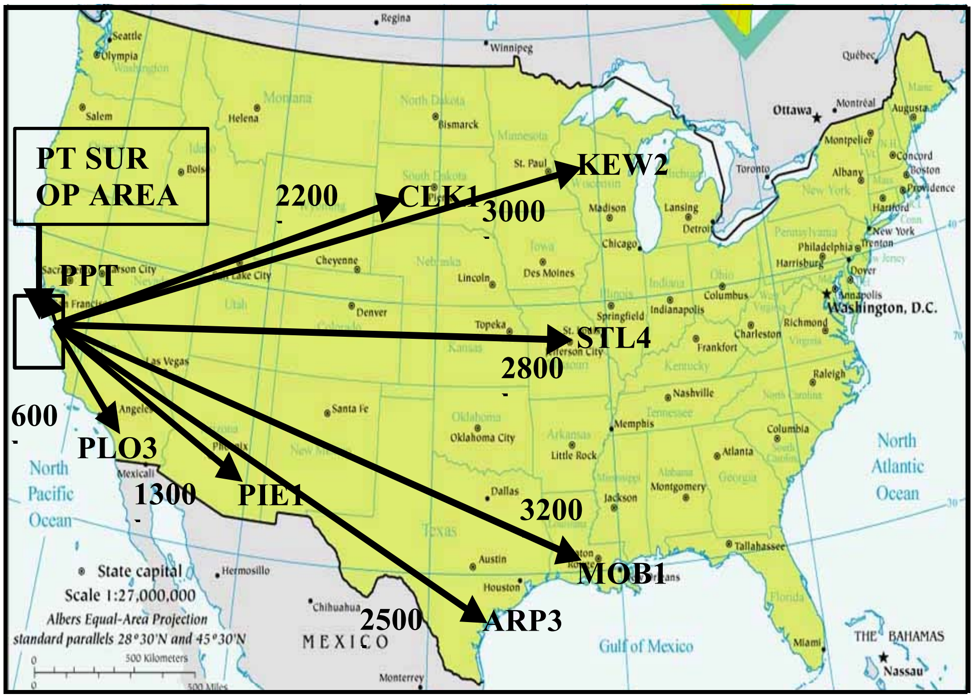

Figure 9. CORS Sites Selected for the Experiment with the Nominal Distance from Monterey (in km) (After: UT, 1999)

The equipment used in the experiment is listed in Table 1.

Table 1. Experiment Equipment List

Site	Receiver Type	Agency
PT SUR	Ashtech Z12	Naval Postgraduate School (NPS)
NPS	Ashtech Z12	Naval Postgraduate School
Aransas Pass	Ashtech Z-XII3	U.S. Coast Guard DGPS
Clark	Ashtech Z-XII3	U.S. Coast Guard DGPS
Keweenaw	Ashtech Z-XII3	U.S. Coast Guard DGPS
Mobile	Ashtech Z-XII3	U.S. Coast Guard DGPS
Pie Town	Rogue SNR-8000	International GPS Service
Point Loma	Ashtech Z-XII3	U.S. Coast Guard DGPS
Pigeon Point	Ashtech Z-XII3	U.S. Coast Guard DGPS
East ST. Louis	Ashtech Z-XII3	U.S. Army Corps of Engineers

Selecting sites that utilized similar equipment and operated under control of the same agency reduced experimental variability. The equipment setup on the ship was laid out to minimize adverse effects due to signal multipath problems. The GPS antenna was placed high on the ship's mast and near the centerline to minimize interference from reflective surfaces.

The Table 2 lists the latitude, longitude, and ellipsoidal height, or altitude, for the antenna's L1 phase center for each CORS station. The nominal range is the approximate distance, in kilometers, between the reference station and ship. The reference datum for the coordinates was North American Datum 1983, NAD83, (Epoch 2002.0) transformed from the International Terrestrial Reference Frame 2000, ITRF00, (Epoch 1997.0) position in March 2002. The positions are the official coordinates posted on the CORS website and the transformations were performed by NGS. Additional information about the derivation of these positions is available at http://www.ngs.noaa.gov/CORS /Derivation.html.

Table 2. CORS Location Information

Site Name	Site ID	Latitude	Longitude	Ellipsoid Height (m)	Nominal Range (km)
Aransas Pass, TX	ARP3	27 50 18.0N	097 03 32.2W	-15.2	2500
Clark, SD	CLK1	44 56 08.2N	097 57 38.4W	416.1	2200
Keweenaw, MI	KEW2	47 13 38.2N	088 37 26.8W	164.7	3000
Mobile, AL	MOB1	30 13 39.0N	088 01 26.8W	-17.1	3200
Pietown, NM	PIE1	34 18 05.4N	108 07 08.1W	2348.8	1300
Point Loma, CA	PLO3	32 39 55.5N	117 14 34.9W	-21.8	600
Pigeon Point, CA	PPT1	37 11 13.5N	122 23 23.8W	8.5	100
East ST. Louis, IL	STL4	38 36 40.7N	089 45 32.0W	168.8	2800

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IV. ANALYSIS

A. BASIS OF ANALYSIS

Military applications often use dual-frequency receivers to provide more accurate measurements than stand-alone receivers. Figure 10 portrays a conceptual representation of a notional platform's actual versus GPS track. The tracks depict positions over time. The actual track is the platform's true position. The GPS track represents a stand-alone GPS receiver-derived position. The difference between the two tracks is the position error. Differential GPS offers a means to resolve this position error by utilizing residual of measurement corrections from reference stations.

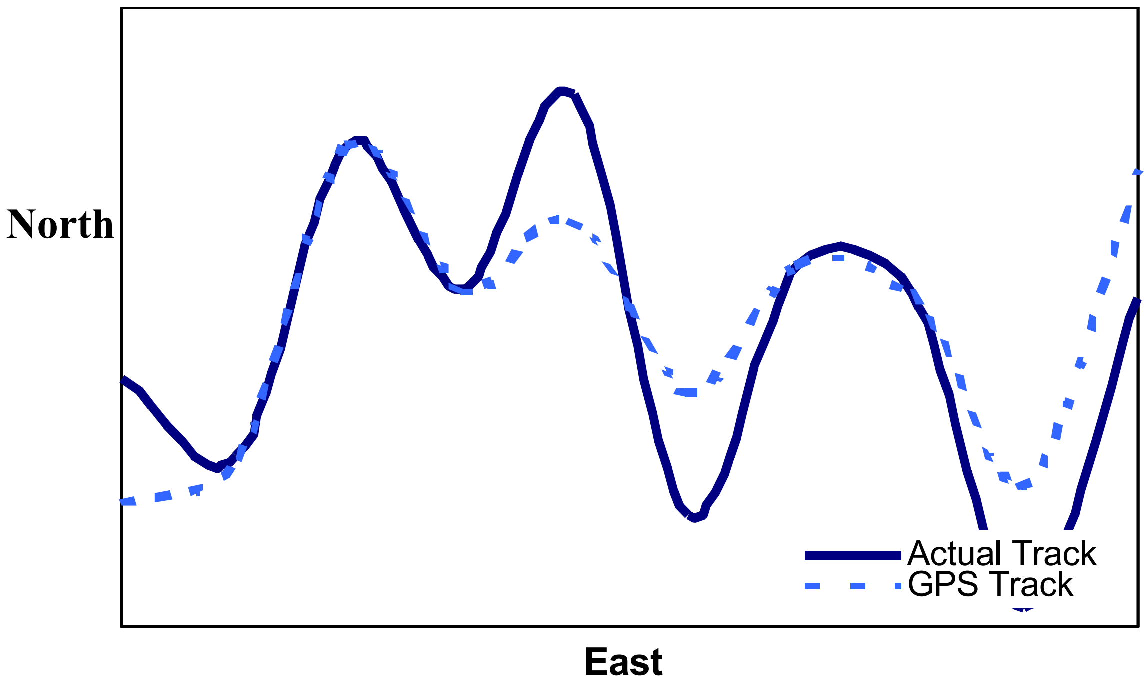


Figure 10. Conceptual Representation of the Problem depicting the Actual Track and the GPS Track. Gaps between the tracks represent position errors.

The data analysis focused on the disparity between a roving receiver's true position and the differentially-corrected GPS position.

B. PRACTICAL APPROACH

Differential GPS (DGPS) incorporates residuals of measurement from reference stations in order to compute positions in real-time. The concept of DGPS is based on the premise that receivers in the same area will experience similar measurement errors.

Reference stations compute the adjustments that are applied to the user's pseudo-range measurements to calculate positions. Differential processing was not performed in real-time since the correction data was not available until after the experiment was completed.

Rather than reprocessing the entire dataset to generate differential positions using every reference station each time, the practical approach was to contrast the ship's residuals of measurement with a reference station's residuals. This method addresses the problem equivalently because the differences in measurement errors represent the deviations in positions. Examining these differences reflects how well that reference station performed at predicting the position errors for the ship.

1. Overview

The basic process involves applying range measurement corrections in the measurement domain then observing the effects in the solution domain. The measurement domain refers to applying corrections in the raw data pseudo-range measurements. The solution domain relates to the position solution error in North, East, Up coordinates. Figure 11 illustrates the block diagram for the basic process starting with the raw data through to the position error.

The process began with the extraction of the residuals of measurements, for each satellite in view, for each timeline, using the raw data from the ship and the truth trajectory. These residuals represented the errors from the stand-alone GPS solution. This was the status quo solution and formed the basis for further comparison of the value of the reference station corrections.

The next step of the process was to generate residuals of measurement for the reference stations. The reference station correction residuals were differenced from the stand-alone residuals while in the measurement domain. Solution errors were derived using the position determination techniques described in Chapter II. The errors corresponded to the deviation between the truth trajectory and the derived trajectory using reference station corrections.

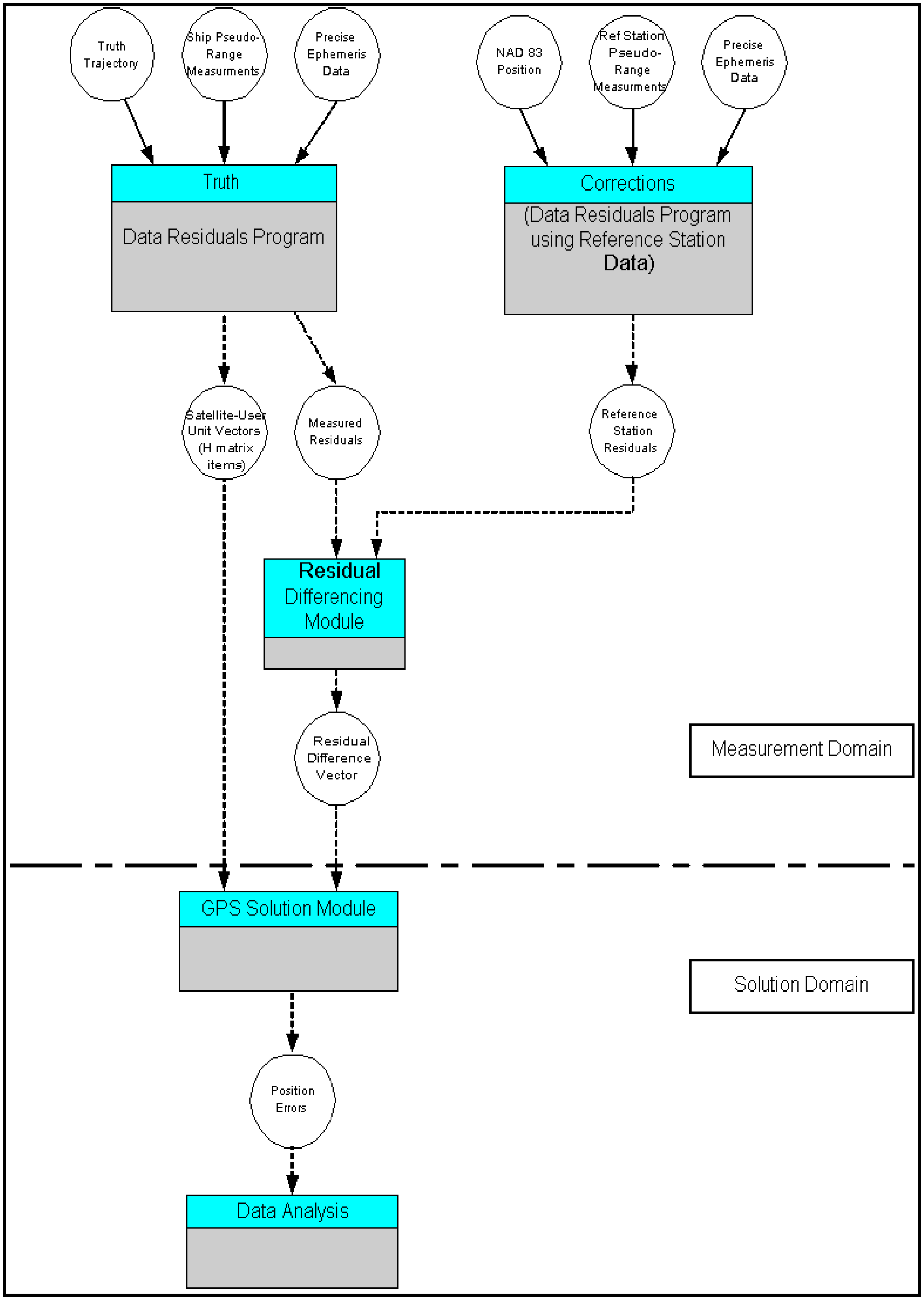


Figure 11. Block Diagram of the Practical Approach

2. Detailed Description

a. Truth Trajectory

The data collected during the PT SUR experiment formed the basis for establishing the truth trajectory. An accurate reference trajectory was necessary to assess the usefulness of the reference station corrections. Ashtech Z12 receivers collected dual-frequency raw data in one-second intervals. One-second intervals were chosen to capture the effects of the pitch and roll of the ship. Processing the same data through two separate GPS solution programs and comparing the results validated the truth trajectory.

The Ashtech Precise Differential GPS Navigation and Surveying Program, PNAV, was used to derive the precise relative positioning between the static receiver located at the Naval Postgraduate School and the mobile receiver on the PT SUR. PNAV performed differential processing on the data collected simultaneously by both receivers. Each time segment of raw data was checked for errors. Valid data was incorporated into the Kalman filter to generate a solution for that time segment. A Kalman filter-smoother program processed the data from the beginning of the data and moving forward in time then reprocessing the same data backwards in time. The two solutions were averaged together which allowed for computing accurate solutions at extended range between receivers.

The GPS Kinematic Positioning Program, KINPOS, developed by Dr. G. L. Mader, (Mader, 1998) provided a means for comparing the accuracy of the PNAV results. This program was run in the rapid-static mode rather than the kinematic mode because of the volume of raw data. Running KINPOS in the kinematic-mode was time intensive requiring several hours to process six hours of data.

The following plots demonstrate the differences between the two solutions in North and East directions. The two solutions agreed within one meter for most of the time segments thus validating the trajectory. However, the KINPOS rapid-static mode solution was not as accurate as the PNAV solution. The average value of the error in the East direction was higher than that of the North error.

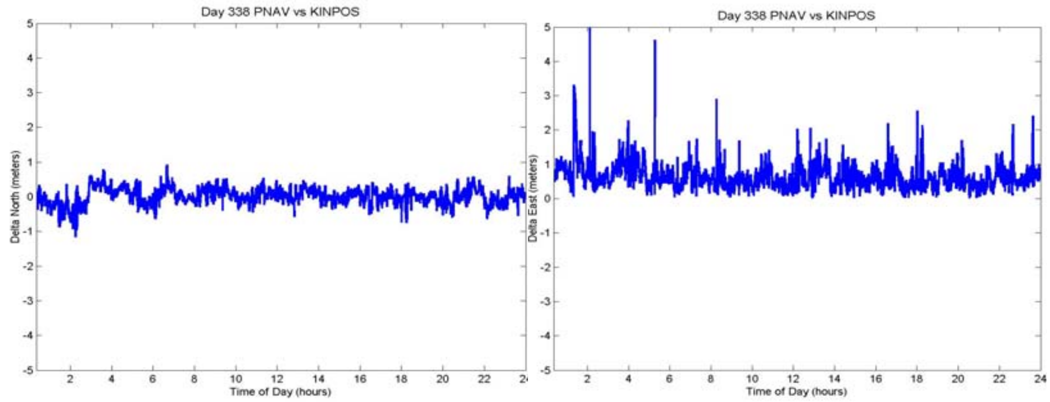


Figure 12. North and East Differences between the PNAV Truth Trajectory and the KINPOS (rapid-static mode) Truth Trajectory

The differences between the solutions were explored further. A small two-hour segment of data was reprocessed using KINPOS in the kinematic-mode.

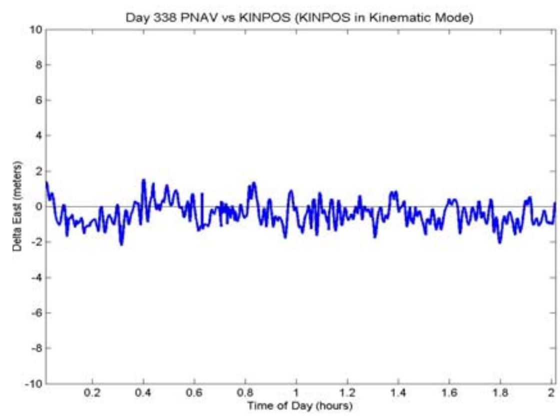


Figure 13. Two-hour Segment of Truth Trajectory using KINPOS (kinematic mode)

This analysis attributed the bias in the solution to differences between the KINPOS rapid-static versus kinematic mode solutions and not due to the truth trajectory. The rapid-static mode did not perform nearly as well as the kinematic mode.

PNAV assigned each time segment of data with a RMS value associated with the fitted residuals for that solution. The RMS value reflects the program's assessment of the position accuracy based on the measurement data and the number of satellite used to compute the solution. The average RMS value for the entire data set was 12 centimeters with a standard deviation of 3 centimeters. This is the highest accuracy that the differential-correction process used in this thesis can achieve.

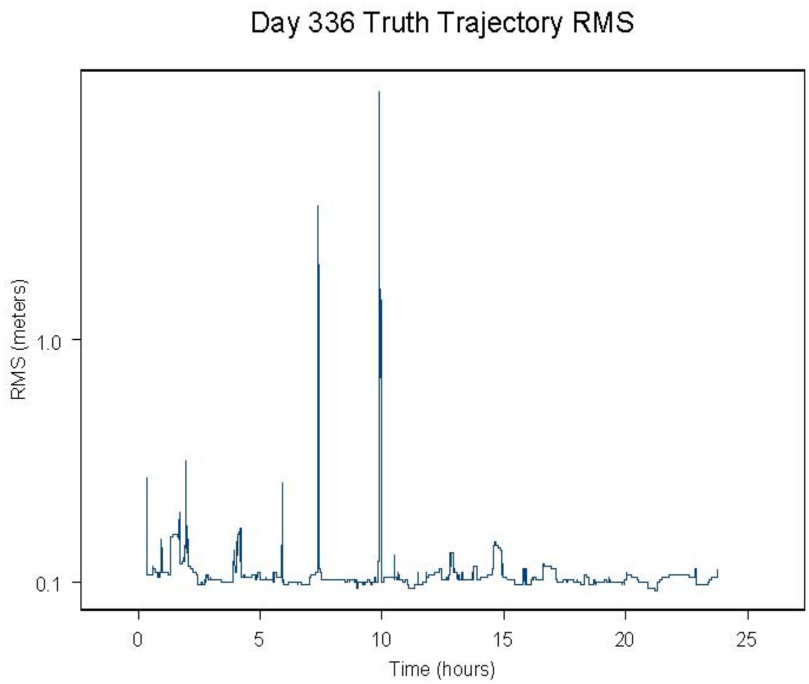


Figure 14. Truth Trajectory Solution RMS Values for Day 336

b. Data Residuals Program

The data residuals program, RXDRESPE.EXE written by Dr. James Clynch, determined the residuals of measurements of the pseudo-range measurements. The same program was used to determine the residuals for the ship and the reference stations. The stand-alone residuals of measurement came from the ship's pseudo-range measurements.

The program inputs were the receiver pseudo-range measurements, precise ephemeris data to determine satellite position, and either the truth trajectory or reference station coordinates to establish the receiver positions. The program generated residuals for the time bias corrections, orbit and clock adjustments, troposphere corrections and ionosphere corrections.

Other outputs from the program were the user-to-satellite unit vectors and the true latitude and longitude positions of the ship. The residuals and the unit vectors were used later to solve for the position error. The ship's latitude and longitude position were used for the conversion of the solution coordinates from Cartesian (x,y,z) Earth-Centered Earth Fixed (ECEF) to North, East and Up coordinates for analysis.

c. Residual Differencing Module

The residual differencing module, in Figure 11, applied the reference station residuals to the stand-alone residuals of measurements that were generated in the data residuals program. The differences between the measurements created the residual difference vector. It is the residual difference vector that reflects the disparity between the truth trajectory and the differentially-corrected trajectory.

The residual difference vector was generated only for those data segments that had matching seconds of the day and satellites. The factors that comprised the residual difference vector were the orbit adjustment, which also included satellite clock bias, an estimate of the troposphere delay and the multipath delay. The error induced by the ionosphere was not included since the data was collected using dual-frequency receivers and cancelled the effect of this error. This mimicked the type of GPS receiver used in military applications.

d. GPS Solution Module

The GPS Solution Module, in Figure 11, performed the solution techniques introduced in Chapter II. The reference station residuals of measurement were applied in the measurement domain vice the position solution domain. This was done since the position errors experienced at the reference station would not correspond to the position errors of the ship. The data analysis determined that the range measurement errors to each satellite were valid at long ranges.

Only one iteration of the solution process was necessary because the residuals of measurement were generated using the actual location of the receiver. The outputs of this module were not position updates but rather position errors. The position error was derived in (x,y,z) coordinates and converted to East, North, Up coordinates for analysis. To prevent computational problems, the GPS solution module checked that at least four satellites were in simultaneous view of both the ship and reference station receivers before computing the solution.

Preliminary analysis of the results showed that high values of DOP induced extreme correction values. As the geometry degraded, spurious solutions resulted. The maximum value for PDOP was set at six, which is typically the limit for

military applications. Limiting the maximum value to six eliminated many wild points while preserving the majority of the data for analysis.

B. DATA PROCESSING

1. Data Format

The data format used for analysis was RINEX format at one-second intervals. The CORS data was provided at 30-second intervals. To correlate this data to the ship's one-second interval data, the National Geodetic Survey provides an interpolation program that takes standard RINEX files as input and generates another RINEX file with interpolated GPS satellite observations at a user-specified rate. This short interval was chosen so that effects of pitch and roll could be assessed.

INTERPO incorporates Neville's algorithm for polynomial interpolation. The interpolation code was adapted from *"Numerical Recipes in C"*, William H. Press, (Press, 1986) and interpolates pseudo-range, Doppler effect, carrier phase, and receiver clock offsets. The algorithm is an 8 point Lagrangean interpolation with each interpolated value derived from four data points on either side in the time series; however, it will not interpolate over gaps in the data (NGS, 2002).

Figure 15 shows the effect of interpolating the data. While interpolation does not add any additional information, it does enable analysis to be performed on the ship's one-second interval data. The plots examine the differentially-corrected position solution errors in the North direction.

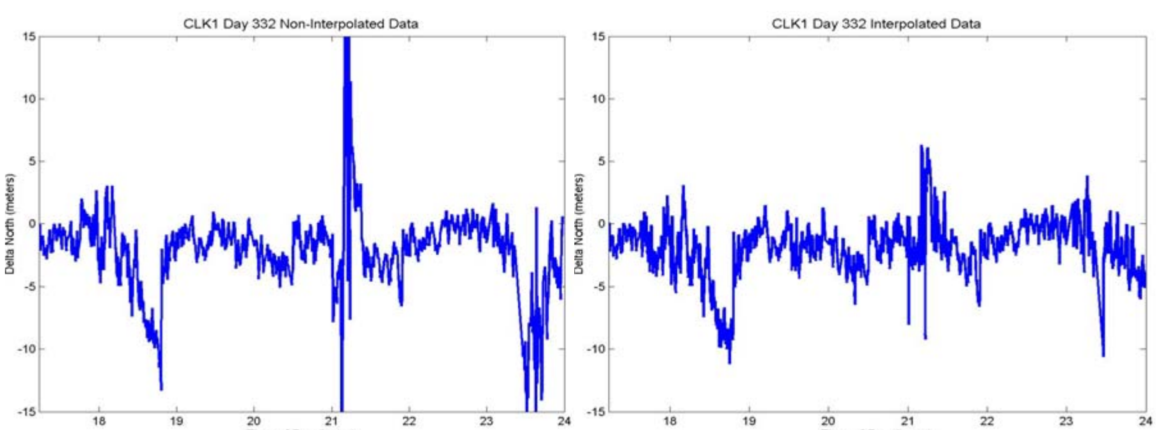


Figure 15. Comparison of Raw Data versus Interpolated Data

Interpolated data captured the same characteristics as the raw data. The interpolated data maintained the same negative bias and the oscillation pattern had peak values similar to those in the non-interpolated data. However, extreme correction points were smoothed thus providing viable data for one-second intervals.

2. Data Selection

The raw receiver data was collected in one-second intervals and created large data files. One day's RINEX Observation file size was approximately 90 MB and the experiment lasted nine days. Eight reference stations were selected to test the hypothesis. The total amount of data approached 10 GB in size. Data reduction techniques were incorporated to trim the data set to a manageable size.

a. Day Selection

The majority of the data reduction was based on selecting which days of data to use for analysis. Days 333, 336, 337, and 338 were chosen because on those days the ship had a mixture in port and at sea time while varying latitude and longitude. This simulated realistic operating conditions for deployed units.

b. Residual Filtering

The residual generation program tagged each residual of measurement with a data quality indicator. Only those satellites that provided good data measurements were used. The residuals of measurements were consistent between successive time periods throughout the experiment. Excessive multipath residual measurements that were caused by receiver phase measurement problems were flagged. These data points were eliminated because they induced erroneous values into the total correction. This selection criterion vastly improved the quality of the generated solution while removing fewer than 1000 satellite measurements per day due to high multipath errors. This was approximately .1% of the data (86400 seconds in a day with an average of seven satellites per time segment).

C. DATA ANALYSIS

The scope of the analysis focused on answering the questions:

- Is the correction process feasible at ranges up to 3000 km?
- How accurate is this process?

- What are the dominant error factors?

Each question was addressed in this sequence since it was the progression of analysis.

1. Is the Process Feasible at Ranges up to 3000 km?

To answer this question, this thesis explored whether or not it was physically possible to even compute a solution using corrections from reference stations up to 3000 kilometers away. The limiting factors in the analysis of this question were the number of satellites in simultaneous view and the dilution of precision.

The data was visually examined to determine if anything significant appeared by plotting the number of satellites and dilution of precision versus time at short, medium and long ranges to assess the patterns of behavior. Short ranges referred to reference stations that were within 600 km of the ship. Medium range was defined to be 1300 km and long range up to 3200 km away.

The plots exhibited similar characteristics. A sinusoidal pattern for the number of satellites was observed due to orbit characteristics of the GPS system. The values oscillated between five and ten satellites at all ranges. There was a trend of an increasing number of edited points as the range between the reference station and the ship increased.

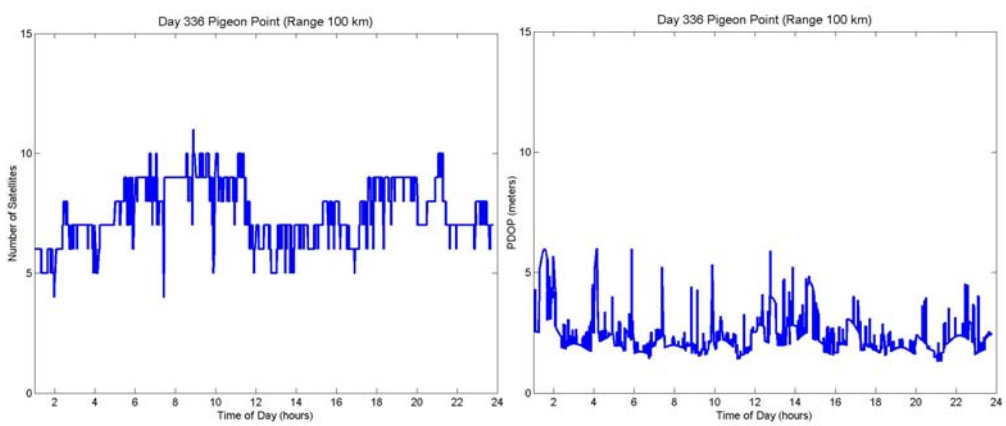


Figure 16. Plot of Number of Satellites used to Compute a Solution and PDOP Short Range (100 km)

Gaps, annotated by circles were used on the plots to indicate either periods of poor raw data measurements or data points that met the criteria for editing. Appendix C contains plots of data availability for each of the reference sites during the conduct of the experiment.

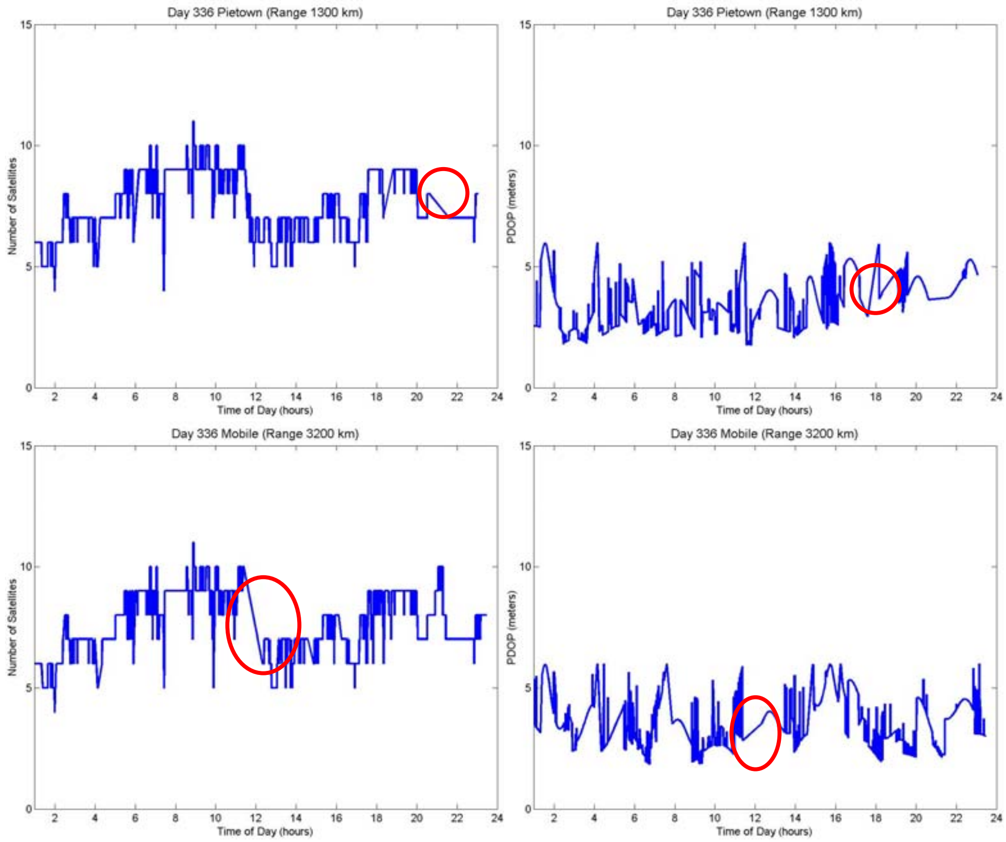


Figure 17. Plot of Number of Satellites used to Compute a Solution and PDOP Medium Range (1300 km) Long Range (3200 km)

Table 3 provided a statistical summary of the mean and standard deviation for the number of satellites in simultaneous view and the position dilution of precision.

Table 3. Mean Values for Number of Satellites & Dilution of Precision

Site	Range	Avg $_{\# Sats}$	StdDev$_{\# Sats}$	Avg $_{PDOP}$	StdDev$_{PDOP}$
Pigeon Point	100	7.48	1.23	2.31	0.83
Pie Town	1300	7.51	1.31	2.97	1.01
Keweenaw	3000	7.57	1.28	3.38	1.06
Mobile	3200	7.7	1.26	3.51	0.99
Stand Alone	-	7.81	1.34	2.27	0.79

The means and standard deviations support the claim that the process is feasible at extended ranges. The mean and median number of satellites visible were approximately seven for all ranges. The dilution of precision showed an increasing trend with distance. However, these values do not tell the entire story because they do not include the effects

of data points that were edited. Other measures of effectiveness were explored by calculating the ratio of points that met the edit criteria in the GPS Solution Module versus the total number of data points.

a. *Minimum Number of Satellites and Dilution of Precision*

Evaluating the ratios:

(1) (# Points edited due to < 4 satellites) / Total # points

(2) (# Points edited due to DOP > 6) / Total # points

Table 4. Ratio of Number of Satellites & Dilution of Precision

Site	Range	Total # Data Points	# Sat Edits	Ratio	#PDOP Edits	Ratio	# Total Edits	Ratio
PPT	100	321914	471	0.001	1852	0.006	2323	0.007
PIE	1300	327109	15418	0.047	58591	0.179	74009	0.226
KEW	3000	330045	3441	0.010	28166	0.085	31607	0.096
MOB	3200	330954	7032	0.021	54175	0.163	61207	0.185

In general, the number of edits increased with range, with the exception of the Pie Town data. Analysis of the Pie Town data editing is described later. The analysis of the results revealed that the long-range sites viewed satellites that were below the elevation cutoff angle for the ship's receiver. The model was adjusted to see the effects of subsequently setting the maximum value of DOP to seven, eight then nine and reprocessing the data. The results were that 51% fewer points for KEW were edited when DOP was allowed to be as high as 7 and 30% fewer for MOB. The reduction between seven and eight was not as dramatic, less than 5%.

Table 5. Effects of Higher DOP Values

Max PDOP	Site	Total # Data Points	# PDOP Edits	Ratio of Edits
7	PPT	321914	1352	0.004
8	PPT	321914	1109	0.003
9	PPT	321914	979	0.003
7	PIE	327109	40115	0.123
8	PIE	327109	31569	0.097
9	PIE	327109	27881	0.085
7	KEW	330045	13882	0.042
8	KEW	330045	10599	0.032
9	KEW	330045	9107	0.028
7	MOB	330954	37692	0.114
8	MOB	330954	27784	0.084
9	MOB	330954	25401	0.077

The effects of editing are illustrated below by measuring the percentage of time that the GPS solution module was unable to produce a solution due to an insufficient number of satellites in simultaneous view or because dilution of precision values exceeded the limit. Insufficient numbers of satellites affected the solution process less than five percent of the time and had little effect even at long ranges. The number of PDOP edits was sensitive to small changes in the maximum value. The graph shows that raising the PDOP limit above six caused a drop in the number of edits which reduced the percentage of time that the process did not compute a solution.

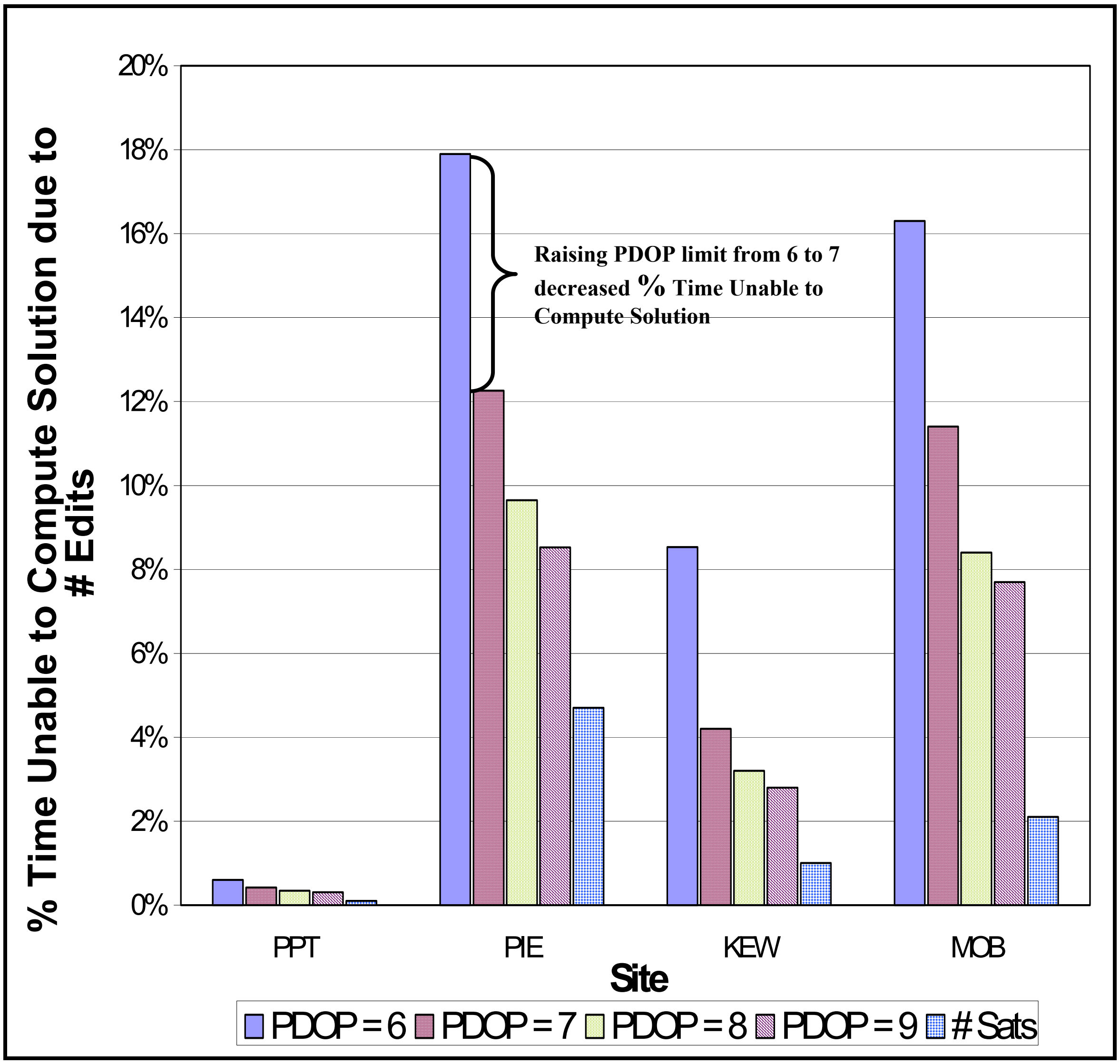


Figure 18. Plot of Percent of Time that the Process was Unable to Compute a Solution Due to Data Editing caused by: Insufficient Number of Satellites or PDOP Limitations

b. Pie Town Analysis

The residual generation program flagged many of Pie Town's measurements as having high values for multipath errors. The number of multipath edits was roughly equal to the number of satellite edits. This suggests that the multipath issue at Pie Town caused the exclusion of several satellite measurements from the computation solutions, which in turn caused a corresponding degradation in the dilution of precision. The causes of the multipath problems may be due to hardware problems at the site.

2. How Accurate is this Process?

This question is answered by comparing the results using reference station corrections at short, medium and long ranges to the stand-alone case. It is possible that at some range, the corrections could induce more position errors than using nothing at all.

a. Plots of Delta North, East and Up Errors

The following plots compare the position errors, in the North and East direction, that the ship experienced using stand-alone GPS. The errors exhibited similar characteristics over the entire dataset. Values fluctuated significantly throughout each day. There is a negative bias in the North direction and, to a lesser extent, in the East. Trying to guide precision munitions using this data might not produce the desired results.

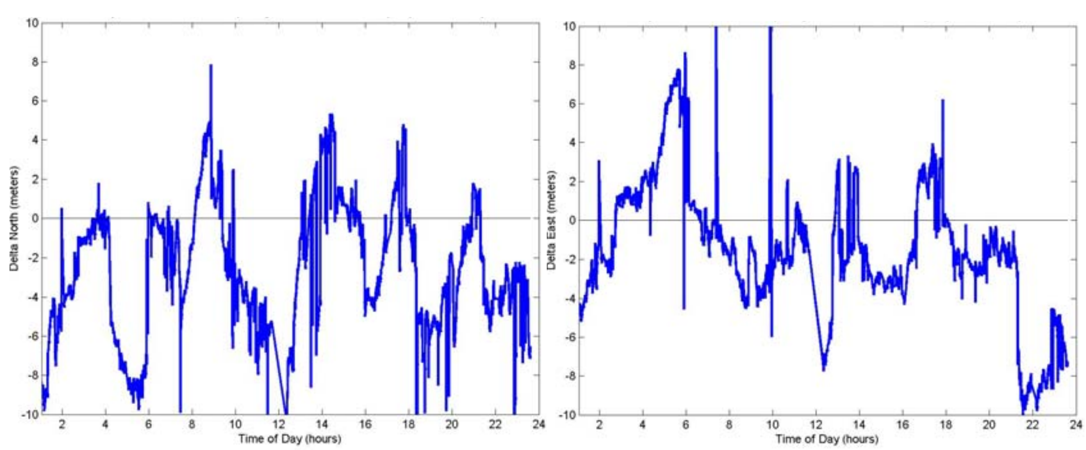


Figure 19. Delta North and East for the Stand-Alone Case (No Corrections Applied)

The subsequent plots illustrate the effects of using measurement corrections from reference stations at varying ranges over a 24-hour period. The delta represents the difference between the true position and the differentially corrected position.

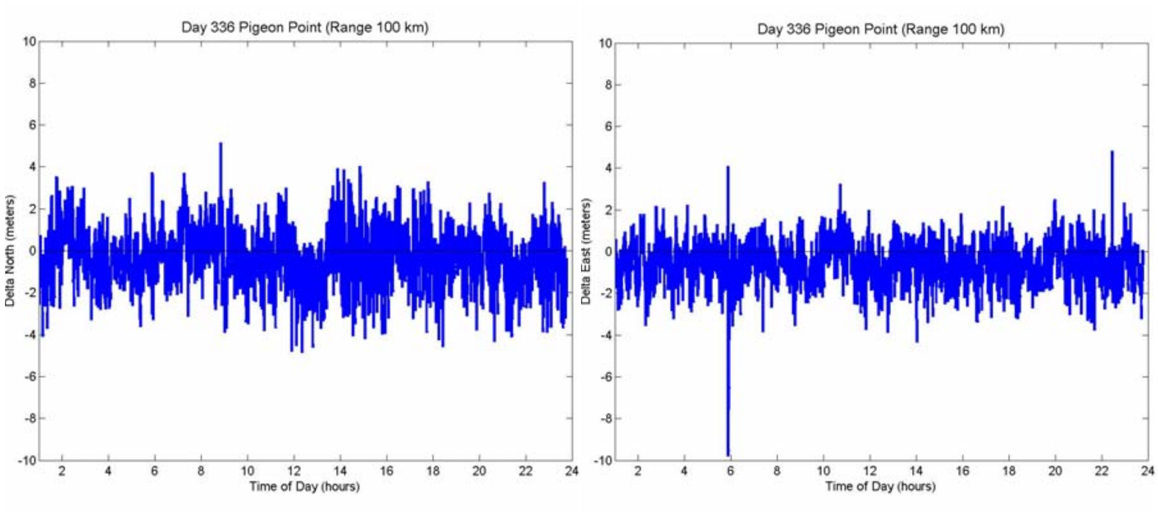


Figure 20. Plots of Solution Errors in the North and East Directions - Short Range

At short ranges, the stations were affected by many of the same circumstances experienced by the ship so the corrections accurately compensated for the measurement errors. The errors were close to zero with a negative bias of less than a meter. The peak values were generally less than +/- two meters.

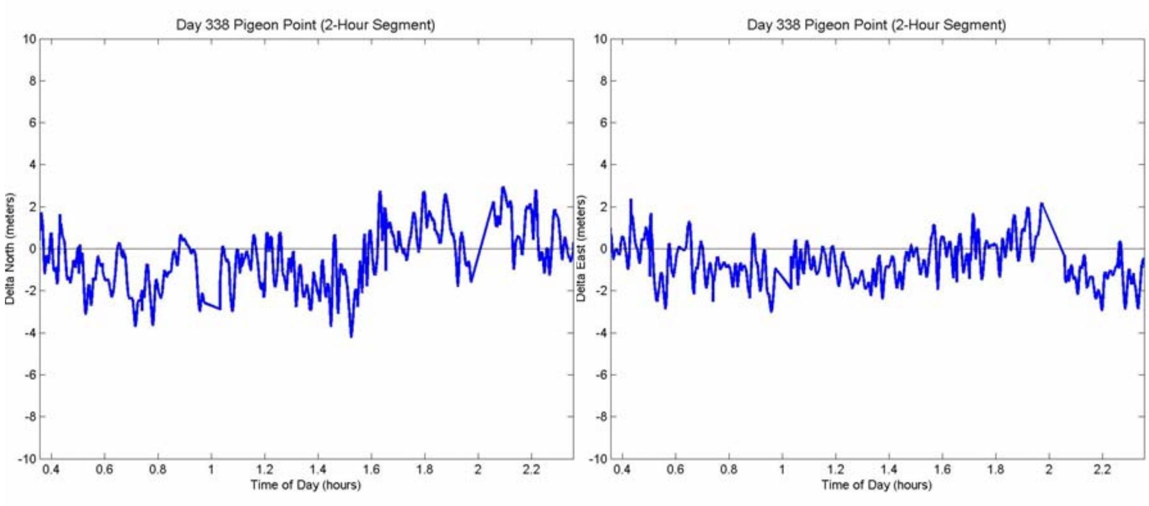


Figure 21. Plots of Solution Errors in the North and East Directions (2-Hour Segment)

The errors on a 24-hour scale seem to radically change between positive and negative values. This is due to plotting a position error for each second of the day. Figure 21 examines a 2-hour segment of the data showing a higher resolution for the errors. The oscillations do not vary significantly from one second to the next, as implied

by the 24-hour plots. This illustrates that it is possible to apply these corrections without causing significant changes in the derived position from one second to the next, which may cause problems with weapon guidance systems.

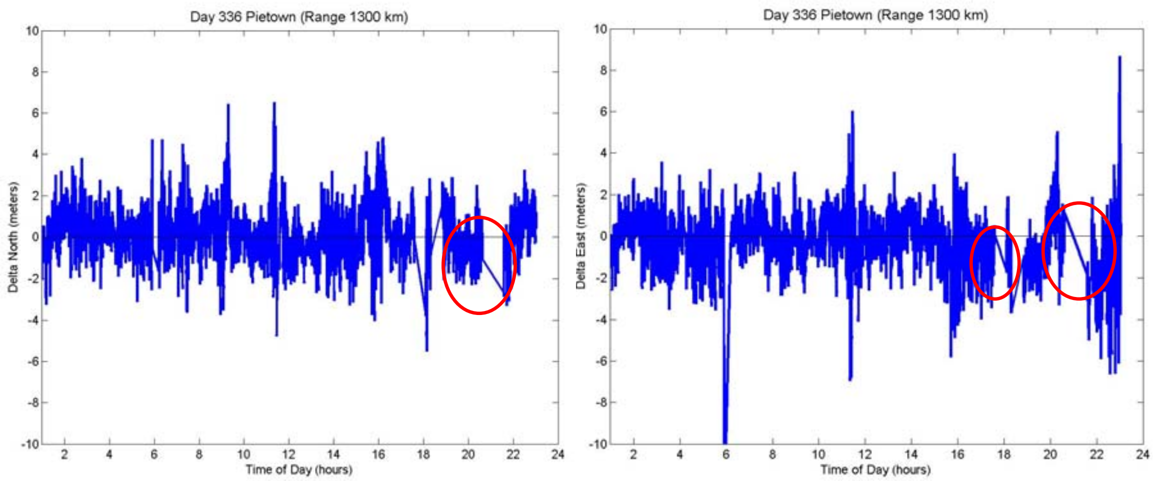


Figure 22. Plots of Solution Errors in the North and East Directions - Medium Range

At medium ranges, the errors were noisier with an increase in the magnitude of the errors. There was an increased number of "spiked" values, but the means were centered around zero. Gaps in the solution, indicated by the diagonal lines in the circles, resulted from data filtering due to either equipment outages, excessive multipath errors (-99 meters), less than four satellites in simultaneous view, or poor dilution of precision values (greater than six).

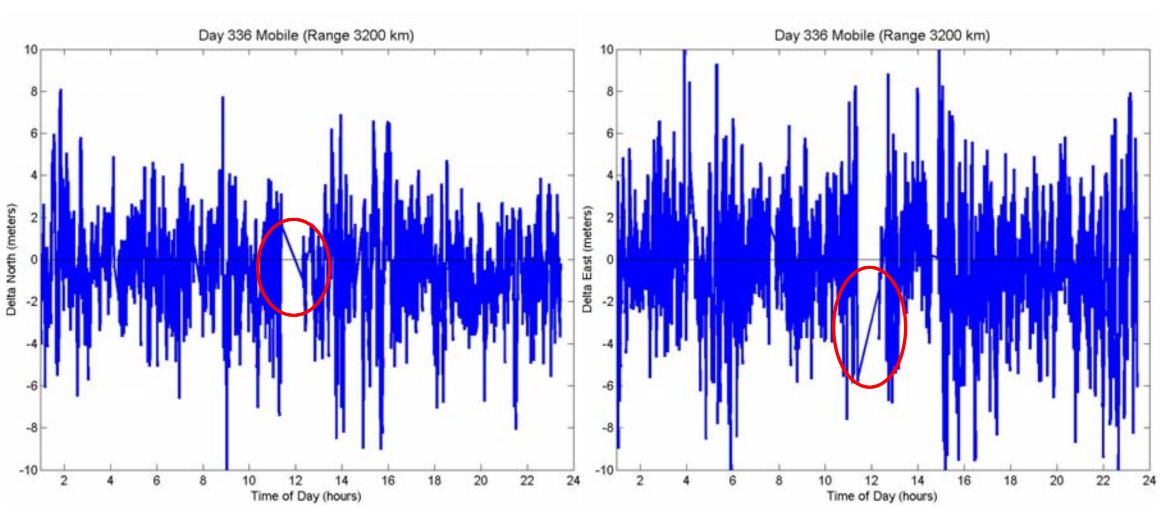


Figure 23. Plots of Solution Errors in the North and East Directions - Long Range

At long ranges, approximately 3000 km, the errors became very noisy compared to the errors at shorter ranges. The means were still centered around zero, however the standard deviations increased significantly exceeding two meters. The resultant position errors at this extended range were high, but still much lower than the stand-alone case.

b. Probability Density Functions of Delta North and East Errors

The histograms for the stand-alone GPS solution show the varying characteristics of the position errors when using the current process without applying reference station corrections. The North and East position errors were negatively biased and had a large spread of values. The position errors in the North direction were flat in the center with the distribution of errors being essentially the same in the range between minus five to zero meters. The position error in the East direction had a smaller region where the distribution was about the same, from minus three to one meters, but this still did not provide an accurate solution.

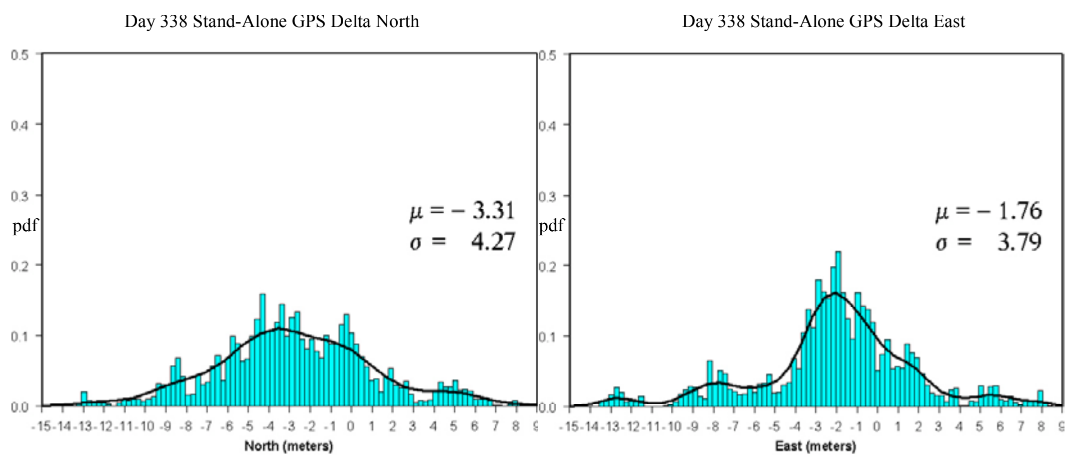


Figure 24. Probability Density Function Plots for Stand-Alone GPS Delta North and East Position Errors (μ – Average Error in meters, σ – Standard Deviation in meters, pdf - in density/meter)

The following plots show the probability density functions (pdf) for the position errors using corrections from short, medium and long-range reference stations. The histograms appear to be approximately normally distributed with means near zero. Slight perturbations in the tails were caused by extreme outliers and affected normality. These values were not deleted because the individual values that were used to generate the solutions did not meet the criteria for filtering.

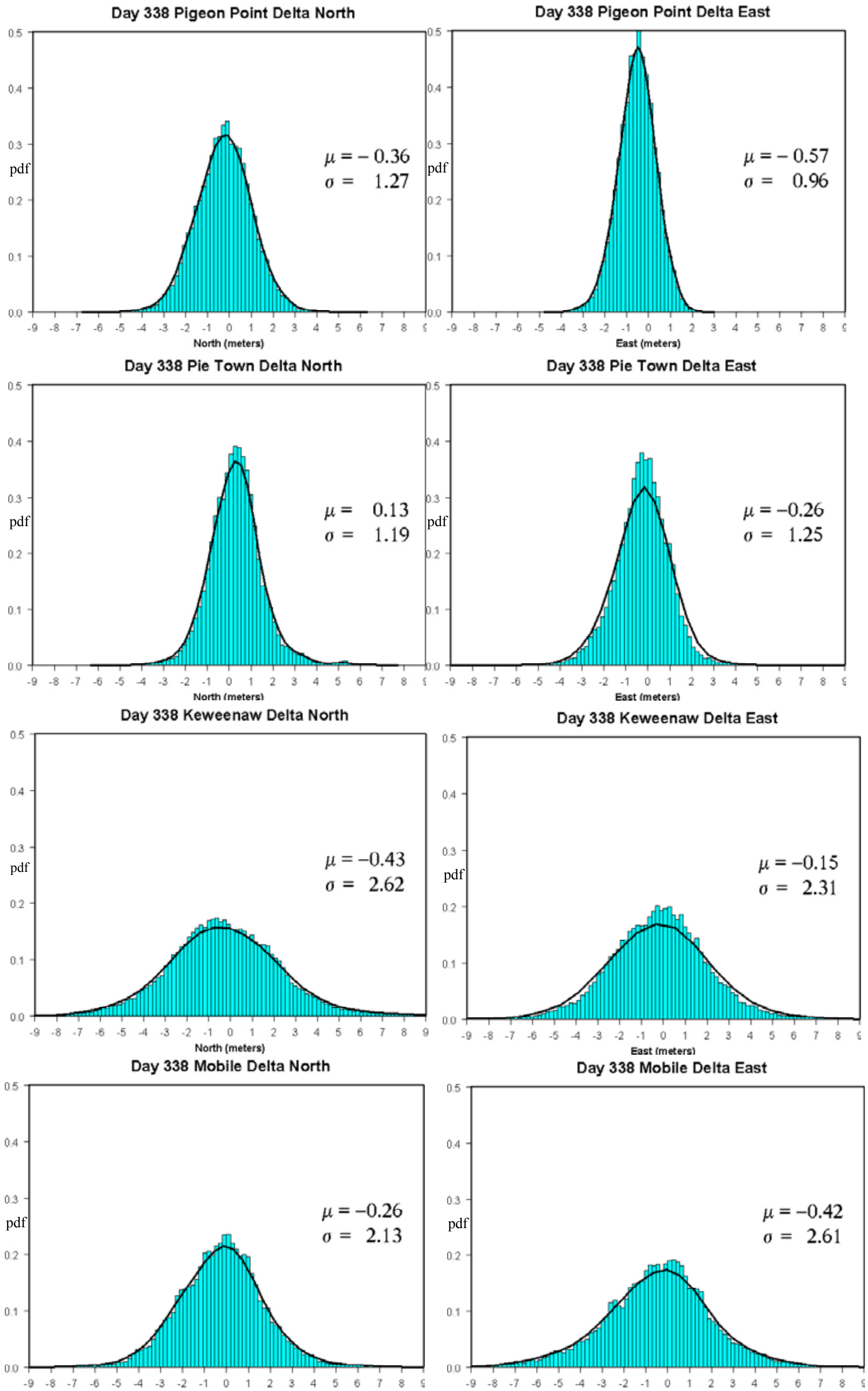


Figure 25. Probability Density Function Plots for Short, Medium and Long Range Reference Stations Delta North and East Position Errors (μ − Average Error in meters, σ − Standard Deviation in meters, pdf - in density/meter)

At short and medium ranges, the means were near zero and had similar standard deviations. However, the Pie Town graphs may be a little deceiving since high values for the multipath errors caused many data points to be filtered out. The variance was smaller in these ranges than the long-range sites. The long range plots further support the increased variability of the errors as range increases. Notice that the variance increases with range. This is consistent with the line plots above.

c. Cumulative Distribution Functions

The following graphs present the cumulative distribution functions (cdf) for each reference station and demonstrate how well one can expect to perform corrections at various ranges. For example, the probability of having an error of less than two meters in the North direction using Pigeon Point is approximately .85, the function value at +2 meters is .95 and the value at -2 meters is .1.

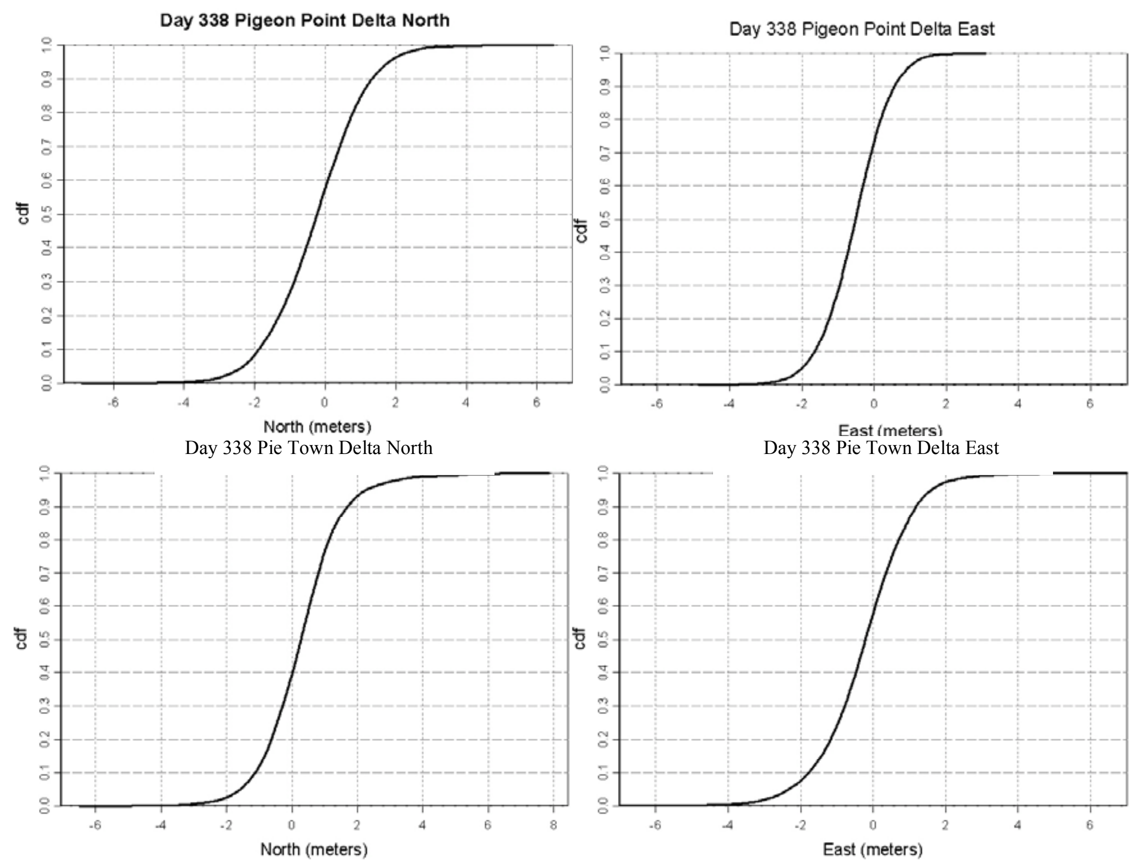


Figure 26. Cumulative Distribution Function Plots for Short and Medium Range Reference Stations

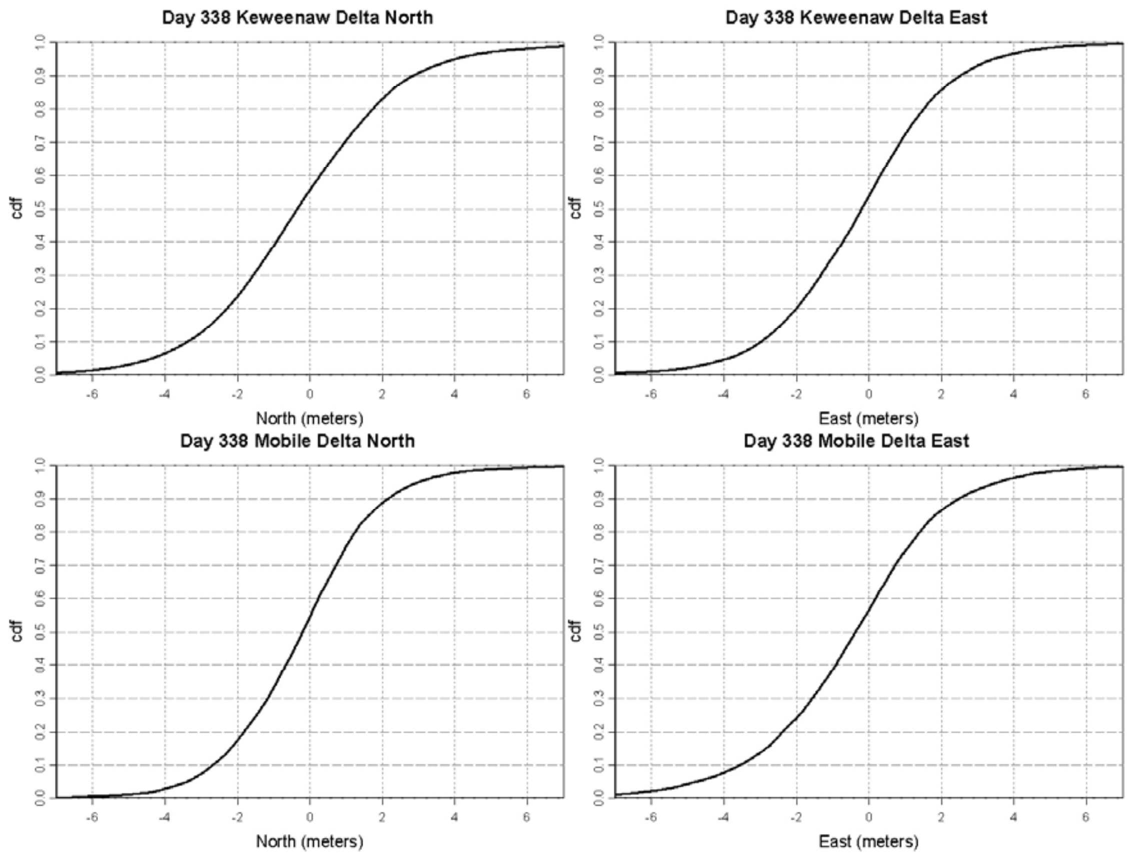


Figure 27. Cumulative Distribution Function Plots for Long Range Reference Stations

d. Analysis of the Standard Deviations of the Errors

The mean values for the process were less than one meter for all the reference station ranges. The standard deviation values remained less than 1.5 meters up to a range of 2200 km. There is a trend of increasing standard deviation at ranges beyond 2200 km. There is a "spike" at 2500 km that does not seem to fit the pattern exhibited by the other sites.

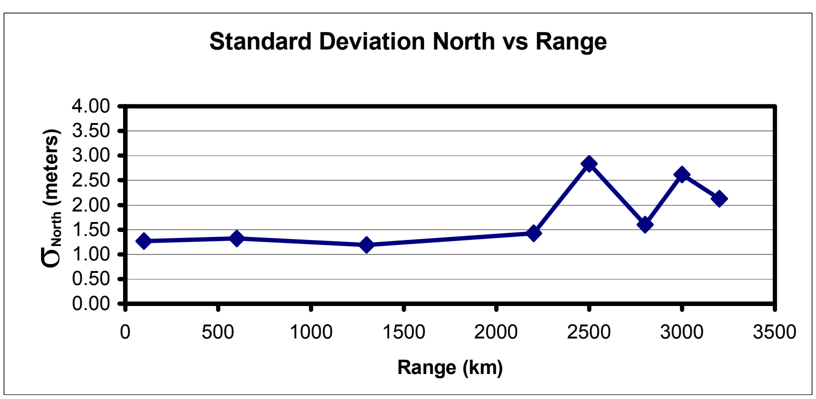


Figure 28. Standard Deviation of the North Solution vs. User-Reference Station Range

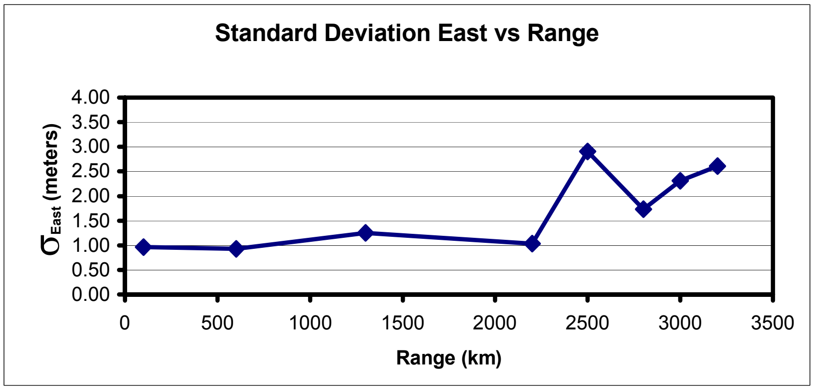


Figure 29. Standard Deviation of the East Solution vs. User-Reference Station Range

3. What are the Dominant Error factors?

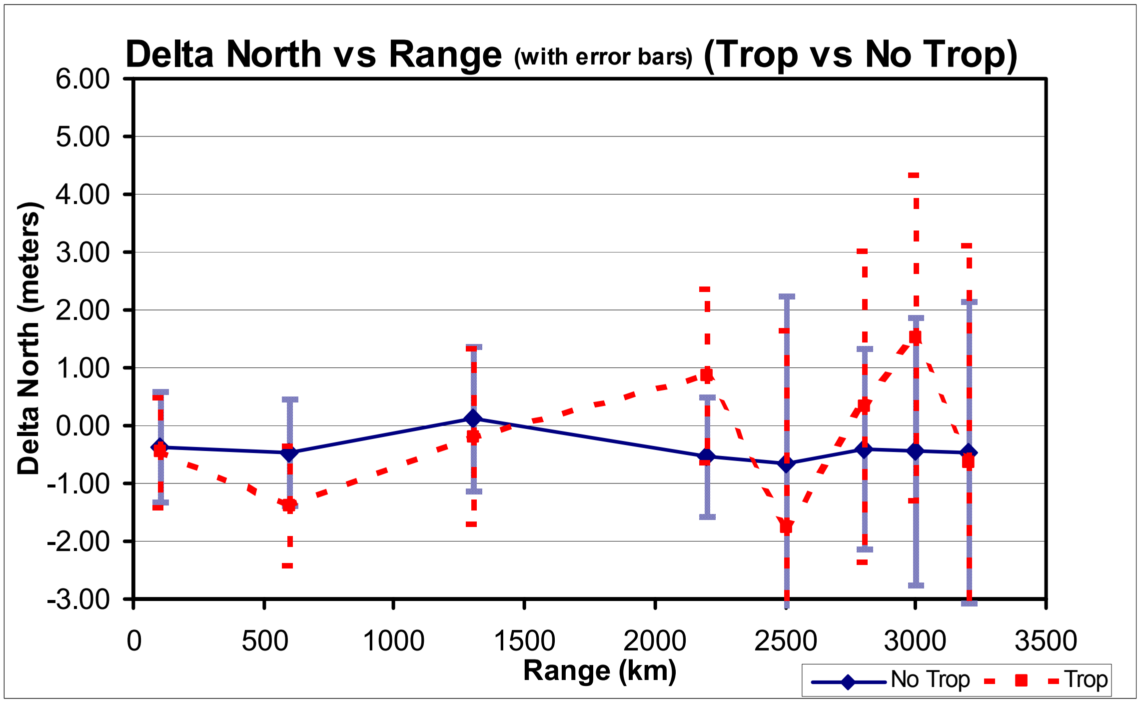
a. Troposphere Effect

The troposphere effect induced the largest magnitude of bias into the position solution. Figure 30 compares the experiment's average solution values for days 333, 336, 337, and 338, in North and East. Two cases were plotted showing the estimated troposphere correction and a hypothetic model that perfectly estimated the tropospheric error.

The troposphere was modeled using Black's Algorithm (Black, 1978) in the residual generation module. The model required temperature, barometric pressure and humidity inputs. The hypothetic model for the troposphere meant that the residuals of measurement for the troposphere were not included as corrections in the solution process. This equates to the reference station troposphere values exactly canceling out the ship's troposphere effect, thus being perfectly modeled.

The solution errors computed in the North direction did not fit any pattern for either model. Error values increased at some ranges and decreased at others. This indicated that a fixed bias could not compensate for the errors in the North.

The solution errors in the East direction increased as the range increased for the troposphere model. This suggested that there was a linear relationship with range. It would be possible to add a bias to the East solution to compensate for the modeled troposphere that follows the trend of the data. The perfect troposphere model showed a negative bias with range.



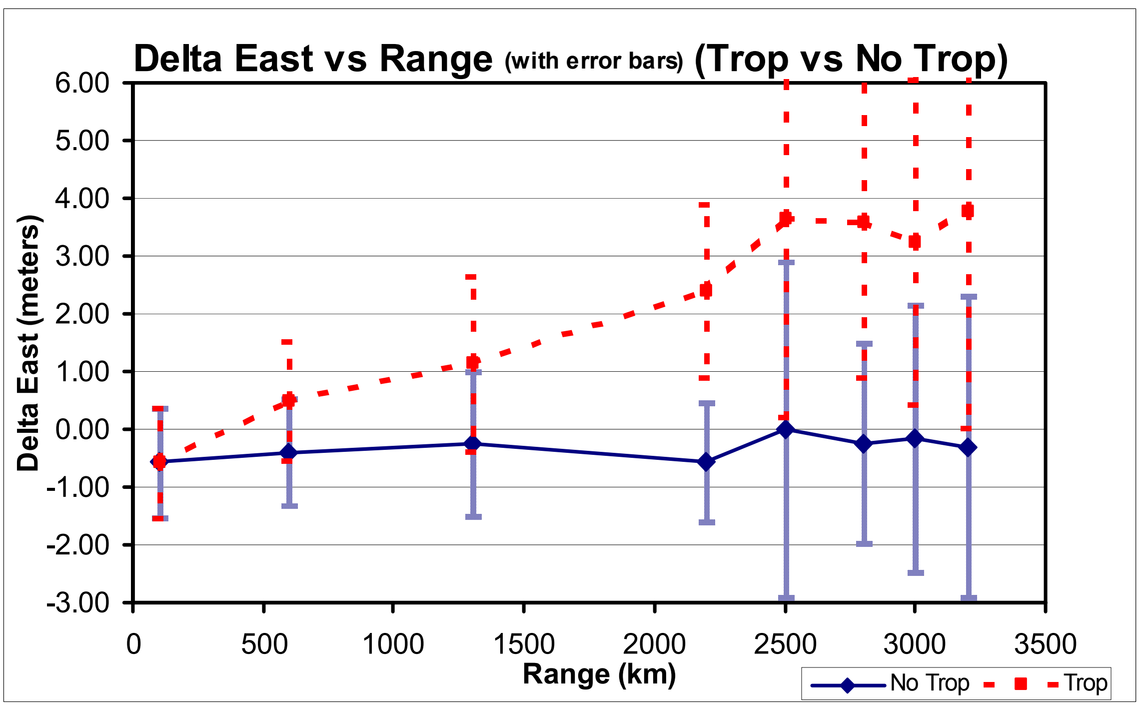


Figure 30. Mean Delta North and East for Days 333, 336-338 versus User-Reference Station Range Effects of Troposphere Modeling (with One Standard Deviation Error Bars)

Temperature, barometric pressure and humidity were the parameters used to model the troposphere effect, ρ_{trop} .

The troposphere effect is determined as follows:

$$\rho_{trop} = \rho_{zenith} * Q(\xi)$$

where:

$$\rho_{zenith} = \rho_{dry} + \rho_{wet}$$

ρ_{zenith} is the component of the troposphere error for a satellite at zenith. $Q(\xi)$ is the obliquity factor and compensates for the elevation angle (ξ) between the satellite and receiver. ρ_{dry} is a function of temperature and pressure and accounts for 90% of the troposphere error (Rizos, 1999). ρ_{wet} is dependent on temperature, pressure and relative humidity.

Each site's weather parameters varied significantly throughout the day. The model incorporated only one set of weather parameters to represent the entire day for modeling the effects of the troposphere. The same temperature of 20 degrees Celsius and 50 percent humidity values were used for each reference station to limit the number of uncontrolled parameters. The barometric pressure values were obtained using the National Oceanic and Atmospheric Administration's Publication of U.S. Standard Atmosphere and were based solely on the reference station's altitude (NOAA, 1976).

Further examination of the parameters used to compute the troposphere correction factor was conducted to see if any effects could be isolated. The troposphere model was re-run to see the impact each parameter had on the correction factor. Extreme values were selected for one parameter at a time while holding the others constant. The values for the correction factors were essentially the same when varying the temperature and humidity. Barometric pressure had some influence causing the correction factor values to decrease as the barometric pressure decreased.

Figure 31 shows the difference in the correction factor caused by changing pressure from 1000 mbar, nominal sea level pressure, to 760 mbar, the Pie Town pressure at an elevation of 2348 km. At the same elevation angle, there was a slight reduction in the correction factor when the barometric pressure was lowered while holding all other factors constant. Differences in reference station altitudes induced minimal biases into the solution errors.

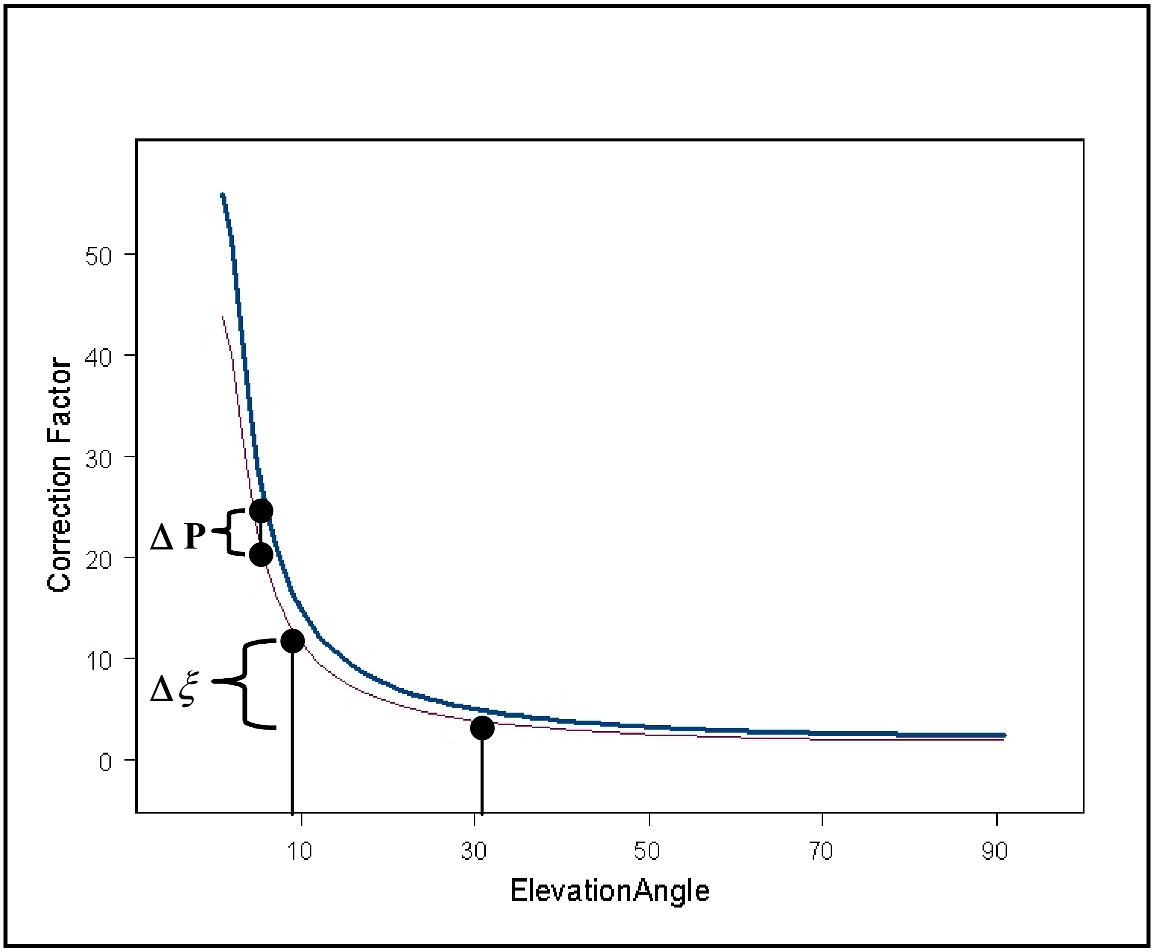


Figure 31. Change in Troposphere Correction Factor due to Changes in Barometric Pressure (ΔP) versus Changes in Satellite Elevation Angle ($\Delta\xi$).

A satellite that is directly above the user receiver is at a different elevation angle to the reference receiver. The correction factor at the reference station is based on its elevation angle to the satellite while the user correction factor is based on its angle. Holding all other parameters constant, changing the elevation angle caused a large change in the correction factor. The troposphere model was more sensitive to changes in satellite elevation angles despite the weather parameters chosen for the model.

b. Multipath Errors

Extreme values for multipath errors, in excess of 30 meters, were filtered out before solving for the position errors. Multipath errors induced extraneous values into the computation process. The impact of the multipath effect dominated the corrections from Pie Town causing 22.6% of the data points to be excluded.

c. Tectonic Plate Motion

The datum used to compute the truth trajectory was determined epoch 1991.35. The NGS on-line software, horizontal time-dependent positioning program, HTDP, was used to adjust for tectonic plate motion to correct for differences in the epochs from 1991 to 2002 (NGS, 2002). HTDP enables users to update geodetic coordinates from one date to another. The correction values were 0.40 meters North and -0.28 meters East.

d. Systematic Biases

The basic process contained inherent biases due to the methods used to derive the solutions. Examination of the results showed that the solution was still had approximately a half meter negative bias in the North and East directions even after correcting for known sources of error. These biases degraded the accuracy of the solution.

e. Day Effects

The following graphs show the errors in the North and East direction for each site and each day. The day-to-day means for each site were constant and sub-meter. This eliminated the possibility that the day affected the results of the experiment.

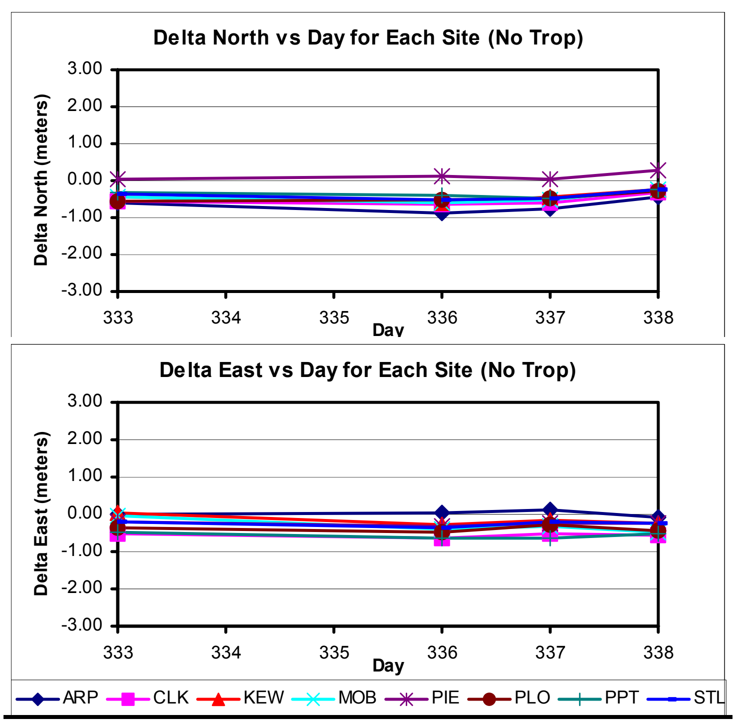


Figure 32. North and East Solution Errors for each Site to Observe Day-to-Day Effects

f. Other Sources of Errors

The data collection experiment and the solution techniques utilized in this thesis were designed to minimize effects of the errors. Using high quality Ashtech receivers minimized measurement errors. Using precise ephemeris data reduced satellite orbit errors. The ionospheric delay is frequency-dependent and was compensated for by using dual-frequency receivers. The clock bias and multipath effects were included as components of the residual generation program and already factored into the solution.

V. CONCLUSIONS

A. GENERAL

This thesis focused on the accuracy and relevance of applying dual-frequency GPS receiver residuals of measurement corrections to compute differential GPS solutions. The correction data is typically valid only in the local area. The process used in this thesis expanded the range between the user and reference station receivers up to 3000 kilometers apart and performed after-the-fact positioning. The process contrasted the ship's residuals of measurement with those of reference stations which assessed the differences in the derived solutions between the positions. The data analysis focused on the stand-alone GPS receiver accuracy versus dual-frequency receiver using differential correction techniques.

This thesis addressed the following questions:

- Is it feasible to utilize correction data at these extended ranges?
- What is the GPS accuracy when using correction data at extended ranges from reference receivers?
- What are the limiting factors in the application of these techniques and why?

The process is feasible and produced accurate results with low two-dimensional RMS error values even at long ranges. The dominant sources of errors were identified and explained. The troposphere effect induced the largest magnitude of bias into the position solution. Further analysis revealed that the troposphere model was more sensitive to changes in satellite elevation angles despite the weather parameters chosen for the model. Multipath errors induced extraneous values into the computation process and were subsequently filtered out. The basic process contained inherent biases due to the methods used to derive the solutions. Examination of the results showed that the solution still had approximately a half meter negative bias in the North and East directions even after correcting for known sources of error.

It appears to be possible to determine GPS solutions for long-range military uses and to use U.S. or Allied GPS assets at long distances from areas of operations to prosecute targets of high interest. The following table summarizes the means and standard deviations of the North, East, Up errors using reference stations at various ranges from the user receiver. The process provided solutions that were more accurate than the stand-alone solution. The stand-alone GPS horizontal root mean square (RMS) accuracy was 5.9 meters while the differentially-corrected RMS accuracy was under 1.5 meters to 2000 kilometers and under 3.0 meters to 3200 kilometers.

The standard deviations from the means increased at ranges beyond 2500 kilometers. There was an anomalous jump in RMS at Aransas Pass, Texas. The data from this site was not eliminated from the process to illustrate the impact of using correction data from sites that generated high variance solutions.

Table 6. Mean, Standard Deviation and Root Mean Square for North, East, Up and 2-Dimensional RMS

Site	Range	Avg$_{N}$	StdDev$_{N}$	RMS$_{N}$	Avg$_{E}$	StdDev$_{E}$	RMS$_{E}$	Avg$_{U}$	StdDev$_{U}$	RMS$_{U}$	Avg$_{2D}$	StdDev$_{2D}$	RMS$_{2D}$
PPT	100	-0.36	1.27	1.320	-0.57	0.96	1.118	-0.04	2.48	2.480	0.68	0.89	1.119
PLO	600	-0.46	1.32	1.397	-0.39	0.93	1.009	0.40	2.74	2.769	0.61	0.89	1.079
PIE	1300	0.13	1.19	1.197	-0.26	1.25	1.276	-2.97	2.91	4.160	0.30	0.95	0.996
CLK	2200	-0.52	1.43	1.522	-0.55	1.03	1.169	-0.65	3.04	3.108	0.77	1.02	1.276
ARP	2500	-0.66	2.84	2.916	0.01	2.91	2.910	-1.18	6.75	6.853	0.67	2.18	2.280
STL	2800	-0.40	1.60	1.649	-0.24	1.73	1.747	-1.28	3.91	4.115	0.47	1.24	1.327
KEW	3000	-0.43	2.62	2.655	-0.15	2.31	2.315	-0.97	5.39	5.477	0.48	1.89	1.949
MOB	3200	-0.45	2.13	2.178	-0.30	2.61	2.628	-1.88	5.13	5.464	0.58	1.82	1.909
Total		**-0.39**	**1.80**	**1.854**	**-0.31**	**1.72**	**1.772**	**-1.07**	**4.04**	**4.303**	**0.57**	**1.36**	**2.543**
Stand-Alone		**-2.78**	**3.41**	**4.400**	**-1.90**	**3.43**	**3.921**	**-0.87**	**8.95**	**8.992**	**5.01**	**3.13**	**5.907**

The differentially-corrected process, introduced in this thesis, produced results that were more accurate than stand-alone GPS at all ranges. Figure 33 supports this assertion by showing the two-dimensional/horizontal position root mean square (RMS) errors versus range. The stand-alone GPS horizontal position RMS error was plotted with its fixed value of 5.9 meters.

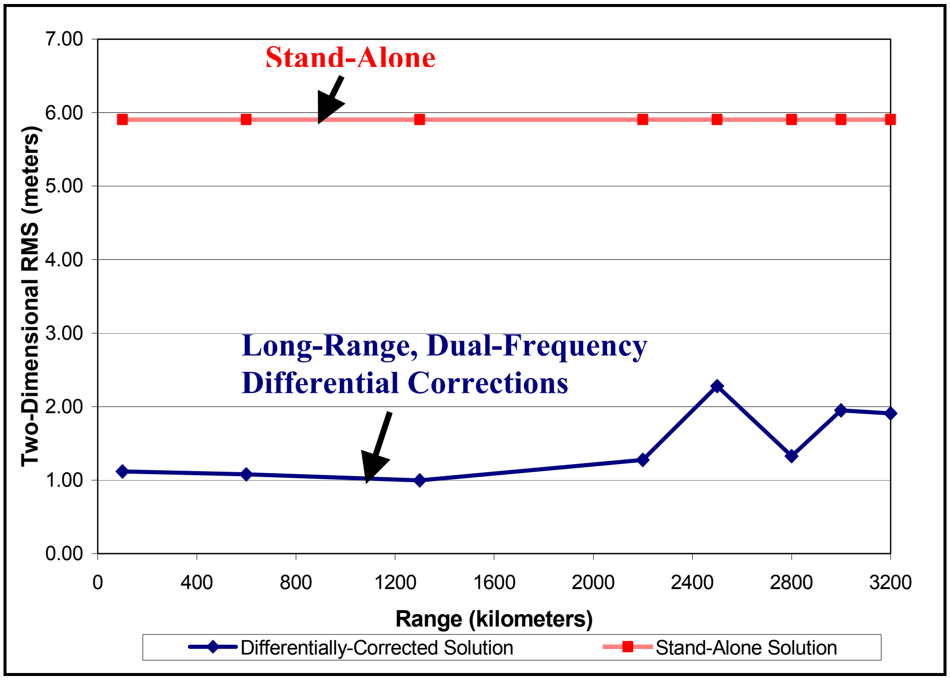


Figure 33. Two-Dimensional RMS for Days 333, 336-338 vs User-Reference Station Range

B. SUMMARY

1. Feasibility

The question of whether or not it was feasible to utilize correction data at extended ranges was answered through the analysis of the number of satellites in simultaneous view of the user and reference station receivers and by examining the dilution of precision. The process required a minimum of four satellites in simultaneous view to compute a solution. There was an average of more than seven satellites in simultaneous view for all reference stations at every range. Overall, the rate of data edits due to an insufficient number of satellites was less than five percent.

Oscar Columbo, author of *Long-Distance Kinematic GPS,* (Columbo, 1998) examined the feasibility when the roving receiver is within 700 kilometers of the reference station. The results of this thesis are consistent with Columbo's research and expanded the range out to 3200 kilometers.

The geometry of the satellites used to perform computations was satisfactory even at long ranges. The ratio of data edits due to poor dilution of precision increased with range. However, less than 20% of the total data points were edited due to PDOP. It was noted that raising the maximum value for PDOP from six to seven yielded a 30%

reduction in the number of edits at 3200 km. The percentages of data edits were sensitive to slight changes in PDOP. Perhaps raising limit above six will preserve a greater proportion of the data at long ranges without adversely affecting solution accuracy.

2. Accuracy

The mean values for the solution errors were low throughout all ranges up to 3200 kilometers. The errors were consistent and had a negative bias throughout the entire range of distances. However, the standard deviations of the errors increased with ranges beyond 2200 kilometers. Cline, Eckl, Mader, Snay and Soler, authors of *Accuracy of GPS-derived Relative Positions as a Function of Inter-Station Distance and Observing-Session Duration*, (Cline, 2001) concluded that accuracy of their solution did not depend on distance, up to 300 km. The results here support that assertion up to 2200 km. However, the standard deviation of the position errors became sensitive to range beyond that distance. The differentially-corrected solution accuracy was still much better than stand-alone GPS.

3. Dominant Error Sources

The largest bias in the position solution was caused by the troposphere effect. The model used to estimate the troposphere effect induced unpredictable biases into the North position solution. The mean values for the errors shifted between positive and negative values as the range increased. The troposphere model showed a bias that increased the East position error with distance. This effect had an approximate linear relationship which could be compensated for.

Further analysis into the variables for the troposphere model revealed that differences in satellite elevation angles caused greater changes in the correction factor than variations in the weather parameters. Differences in reference station altitudes induced minimal biases into the solution. Troposphere models should consider elevation angles when implementing this process.

Multipath problems affected the solution process. Sites with excessive multipath errors experienced significant degradations in solution accuracy. Eliminating data points with high multipath values improved the solution accuracy but resulted in having an insufficient number of satellites to perform computations. Multipath should be an important factor when selecting reference stations for differential corrections.

C. RECOMMENDATIONS FOR FUTURE RESEARCH

1. Extending the Maximum Range Between the User and Reference Stations

The process produced accurate results at 3200 km. The numbers of satellites in simultaneous view were sufficient to perform computations at this range. Future research could explore the cutoff range when there are no longer enough satellites visible.

2. Troposphere Modeling

The analysis of the troposphere revealed that the weather parameters affected the troposphere correction factor to some extent. However, the differences between the elevation angle to the satellite from the user and the reference station had the largest impact. Different troposphere models could be used to see how well all these factors could be predicted.

3. Effects of Dilution of Precision on Solution Accuracy

There was a dramatic reduction in the number of filtered data points when the maximum value for DOP was raised to seven. This thesis did not quantify the impact of including these points on the solution means and standard deviations. Future research could measure the affect on the solution.

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APPENDIX A: CORS SITES

The following is a listing of CORS sites obtained from the NGS website. The columns are divided by: State, Site Name, Site ID, Date Online, Date Offline, Collection Rate, Availability, and Organization.

ST	Site Name	Site ID	online	offline	Rate	*	Agency
AK	Anchorage	TSEA	1999/179	--------	30 sec	H	TSEA
AK	Annette Island	AIS2	--------	--------	30 sec	H	USCG
AK	Annette_Island	AIS1	1996/019	--------	30 sec	H	USCG
AK	Biorka Island	BIS1	2000/080	--------	30 sec	H	USCG
AK	Biorka Island	BIS2	--------	--------	30 sec	H	USCG
AK	Cape Hinchinbrook	CHI1	1996/257	1999/061	30 sec	H	USCG
AK	Cape Hinchinbrook	CHI2	--------	--------	30 sec	H	USCG
AK	Cape Hinchinbrook	CHI3	1999/061	--------	30 sec	H	USCG
AK	Cape Hinchinbrook	CHI4	--------	--------	30 sec	H	USCG
AK	Central	CENA	1998/037	--------	30 sec	H	FSL
AK	Cold Bay	BAY1	1996/036	--------	30 sec	H	USCG
AK	Cold Bay	BAY2	--------	--------	30 sec	H	USCG
AK	Fairbanks	FAIR	1996/024	--------	30 sec	D	JPL
AK	Glennallen	GNAA	1998/189	--------	30 sec	H	FSL
AK	Gustavus	GUS1	1996/106	--------	5 sec	H	USCG
AK	Gustavus	GUS2	1997/021	--------	5 sec	H	USCG
AK	Kenai	KEN1	1996/031	--------	30 sec	H	USCG
AK	Kenai	KEN2	2002/120	--------	30 sec	H	USCG
AK	Kodiak	KOD1	1996/032	--------	30 sec	H	USCG
AK	Kodiak	KOD2	--------	--------	30 sec	H	USCG
AK	Kodiak	KODK	2000/122	--------	30 sec	D	SOPAC
AK	Level Island	LEV1	2001/171	--------	5 sec	H	USCG
AK	Level Island	LEV2	--------	--------	5 sec	H	USCG
AK	Potato Point	POT1	1996/257	1998/120	30 sec	H	USCG
AK	Potato Point	POT2	1997/037	1998/253	30 sec	H	USCG
AK	Potato Point	POT3	1998/245	--------	30 sec	H	USCG
AK	Potato Point	POT4	1999/008	--------	30 sec	H	USCG
AK	Prudhoe Bay	CCPT	2002/043	--------	30 sec	D	BP
AK	Prudhoe Bay	PBOC	2002/043	--------	30 sec	D	BP
AK	Talkeetna	TLKA	1998/189	--------	30 sec	H	FSL
AL	Millers Ferry	MLF1	1996/281	--------	30 sec	H	USCG
AL	Millers Ferry	MLF2	--------	--------	30 sec	H	USCG
AL	Mobile Point	MOB1	1996/100	--------	30 sec	H	USCG
AL	Mobile Point	MOB2	1996/132	--------	30 sec	H	USCG
AR	Dequeen	DQUA	1996/366	--------	30 sec	H	FSL
AR	French Bayou	MEM1	--------	--------	30 sec	H	USCG
AR	French Bayou	MEM2	1995/207	--------	30 sec	H	USCG
AS	Pago Pago	ASPA	2001/224	--------	5 sec	H	ASDC
AZ	Ash Fork	FERN	2000/314	--------	30 sec	D	UNAVCO
AZ	Flagstaff	FST1	2000/229	--------	5 sec	H	USCG
AZ	Flagstaff	FST2	--------	--------	5 sec	H	USCG
AZ	Fredonia	FRED	2000/314	--------	30 sec	D	UNAVCO
AZ	Kingman	KING	2002/091	--------	30 sec	H	KING
AZ	Scottsdale	COSA	1998/258	--------	5 sec	H	CofS
AZ	Tolleson	SRP1	2001/306	--------	5 sec	H	SRP
AZ	Tucson	COT1	2000/004	--------	5 sec	H	CofT
CA	Blythe	BLYT	1995/309	--------	30 sec	D	SOPAC
CA	Chico	CHO1	1999/197	--------	30 sec	H	USCG
CA	Chico	CHO2	2001/291	--------	30 sec	H	USCG
CA	Columbia	CMBB	1997/202	--------	30 sec	D	UCB
CA	Coso Junction	COSO	1998/155	--------	30 sec	D	SOPAC
CA	Durmid Hill	DHLG	1998/155	--------	30 sec	D	SOPAC

CA	East of Colusa	SUTB	1998/155	--------	30	sec	D	UCB
CA	East of San Jose	MHCB	1998/155	--------	30	sec	D	UCB
CA	Goldstone	GOL2	1999/267	--------	30	sec	D	JPL
CA	Goldstone	GOLD	1995/267	1999/267	30	sec	D	JPL
CA	Hercules	OHLN	2002/093	--------	30	sec	D	UCB
CA	Hopland	HOPB	1998/155	--------	30	sec	D	UCB
CA	Laguna Mountains	MONP	1998/155	--------	30	sec	D	SOPAC
CA	Mendocino	CME1	1996/100	--------	30	sec	H	USCG
CA	Mendocino	CME2	--------	--------	30	sec	H	USCG
CA	Near Mammoth Lakes	MINS	1998/204	--------	30	sec	D	USGS
CA	Parkfield	CARR	1998/155	--------	30	sec	D	SOPAC
CA	Petaluma	PET1	1997/098	1997/226	30	sec	H	USCG
CA	Pigeon Point	PPT1	1996/019	--------	30	sec	H	USCG
CA	Pigeon Point	PPT2	--------	--------	30	sec	H	USCG
CA	Pinyon Flat	PIN1	1998/155	--------	30	sec	D	SOPAC
CA	Point Arguello	PAR1	1996/281	1999/036	30	sec	H	USCG
CA	Point Blunt	PBL1	1995/192	--------	30	sec	H	USCG
CA	Point Blunt	PBL2	--------	--------	30	sec	H	USCG
CA	Point Loma	PLO1	1995/192	1996/250	30	sec	H	USCG
CA	Point Loma	PLO2	--------	--------	30	sec	H	USCG
CA	Point Loma	PLO3	1996/250	--------	5	sec	H	USCG
CA	Quincy	QUIN	1996/224	--------	30	sec	D	JPL
CA	San Leandro	CHAB	1998/161	--------	30	sec	D	USGS
CA	Stockton	CNDR	1999/099	--------	30	sec	D	CETI
CA	Temecula	BILL	1998/155	--------	30	sec	D	SOPAC
CA	Torrance	TORP	1998/161	--------	30	sec	D	USGS
CA	Tracy	S300	1999/130	--------	5	sec	H	LLNL
CA	Trinidad Head	TRND	2001/353	--------	30	sec	D	CWU
CA	Vandenberg	VAN1	1999/055	--------	30	sec	H	USCG
CA	West of Yreka	YBHB	1997/202	--------	30	sec	D	UCB
CO	Boulder	DSRC	1999/356	--------	30	sec	H	FSL
CO	Colorado Springs	AMC2	2000/242	--------	30	sec	D	JPL
CO	Granada	GDAC	1996/292	--------	30	sec	H	FSL
CO	Platteville	PLTC	1995/023	--------	30	sec	H	FSL
CO	Pueblo	PUB1	2001/312	--------	5	sec	H	USCG
CO	Pueblo	PUB2	--------	--------	5	sec	H	USCG
CO	Table Mountain	TMGO	1994/227	--------	30	sec	D	NGS
DC	Washington	USNO	2000/173	--------	30	sec	D	JPL
DE	Cape Henlopen	CHL1	1995/166	2002/014	5	sec	H	USCG
DE	Dover	DNRC	1998/084	--------	15	sec	H	DEDP
DE	Reedy Point	RED1	1999/063	--------	5	sec	H	USCG
DE	Reedy Point	RED2	2002/120	--------	5	sec	H	USCG
ES	San Salvador	SSIA	2000/284	--------	30	sec	H	NGS
FL	Cape Canaveral	CCV1	1996/037	1998/216	30	sec	H	USCG
FL	Cape Canaveral	CCV3	1998/216	--------	30	sec	H	USCG
FL	Cape Canaveral	CCV4	--------	--------	30	sec	H	USCG
FL	Egmont Key	EKY1	1996/024	2001/114	30	sec	H	USCG
FL	Egmont Key	EKY2	unknown	2001/114	30	sec	H	USCG
FL	Geiger Key	KYW1	1996/347	--------	30	sec	H	USCG
FL	Geiger Key	KYW2	2001/291	--------	30	sec	H	USCG
FL	Key Biscayne	AOML	1997/365	--------	30	sec	D	NGS
FL	Mac Dill AFB	MCD1	2001/121	--------	30	sec	H	USCG
FL	Mac Dill AFB	MCD2	--------	--------	30	sec	H	USCG
FL	Miami	MIA1	1995/236	1998/154	30	sec	H	USCG
FL	Miami	MIA3	1998/155	--------	5	sec	H	USCG
FL	Miami	MIA4	--------	--------	5	sec	H	USCG
FL	Perrine	RCM5	1994/178	1996/306	30	sec	D	NGS
FL	Perrine	RCM6	1996/306	1998/274	30	sec	D	NGS
GA	Evans	COGA	2000/206	--------	5	sec	H	TRS
GA	Macon	MCN1	2000/081	--------	30	sec	H	USCG
GA	Macon	MCN2	2002/120	--------	30	sec	H	USCG
GA	Marietta	ATL1	2001/078	--------	1	sec	H	SPSU
GA	Savannah Beach	SAV1	1998/337	--------	30	sec	H	USCG
GA	Savannah Beach	SAV2	2002/128	--------	30	sec	H	USCG

GT	Guatemala City	GUAT	2000/216	--------	30	sec	D	NGS
GT	Santa Elena	ELEN	2001/342	--------	30	sec	D	NGS
GU	Dededo	GUAM	1996/272	--------	30	sec	D	JPL
HI	Haleakala	MAUI	2002/054	--------	30	sec	D	PGPS
HI	Hilo	HILO	2002/054	--------	30	sec	D	PGPS
HI	Honolulu	HNLC	2002/054	--------	30	sec	D	PGPS
HI	Kauai	KOKB	2000/108	--------	30	sec	D	JPL
HI	Kokole Point	KOK1	1996/037	--------	5	sec	H	USCG
HI	Kokole Point	KOK2	--------	--------	5	sec	H	USCG
HI	Upolu Point	UPO1	1996/032	--------	5	sec	H	USCG
HI	Upolu Point	UPO2	2002/120	--------	5	sec	H	USCG
HO	San Lorenzo	SLOR	2000/298	--------	30	sec	H	NGS
HO	Teguciagalpa	TEG1	2001/298	--------	30	sec	H	NGS
HO	Teguciagalpa	TEGU	2000/130	2002/081	30	sec	H	NGS
IA	North Liberty	NLIB	1995/267	--------	30	sec	D	JPL
IA	Pisgah	OMH1	1998/283	--------	30	sec	H	USCG
IA	Pisgah	OMH2	--------	--------	30	sec	H	USCG
IA	Slater	SLAI	1999/278	--------	30	sec	H	FSL
IA	Teeds Grove	RIS1	1997/220	--------	30	sec	H	USCG
IA	Teeds Grove	RIS2	--------	--------	30	sec	H	USCG
ID	Boise	IDTD	2001/134	--------	30	sec	D	NGS
ID	Idaho Falls	GTRG	2000/133	--------	30	sec	D	UNAVCO
IL	Libertyville	LCDT	2001/276	--------	15	sec	H	LCDT
IL	Summerfield	STL1	1995/226	1995/229	30	sec	H	USACE
IL	Summerfield	STL2	1995/207	1996/138	30	sec	H	USACE
IL	Summerfield	STL3	1996/210	--------	30	sec	H	USCG
IL	Summerfield	STL4	1998/085	--------	30	sec	H	USCG
IL	Urbana	UIUC	2002/054	--------	5	sec	H	U IL
IL	Winchester	WNCI	2000/153	--------	30	sec	H	FSL
IN	Bloomington	IUCO	2000/128	--------	5	sec	H	INUN
IN	Wolcott	WLCI	1998/321	--------	30	sec	H	FSL
JA	Kingston	JAMA	2000/171	--------	30	sec	D	NGS
KS	Cherryvale	NDS1	2001/038	--------	30	sec	H	FSL
KS	Haviland	HVLK	1996/154	--------	30	sec	H	FSL
KS	Hillsboro	HBRK	1995/113	--------	30	sec	H	FSL
KS	Neodesha	NDSK	1996/249	2000/241	30	sec	H	FSL
KS	Perry	KAN1	1996/256	--------	30	sec	H	USCG
KS	Perry	KAN2	--------	--------	30	sec	H	USCG
KY	Erlanger	ERLA	1996/303	--------	5	sec	H	NCAD
KY	Taylorsville	LOU1	1998/043	--------	30	sec	H	USCG
KY	Taylorsville	LOU2	--------	--------	30	sec	H	USCG
LA	Cocodrie	COCD	2002/024	2002/084	30	sec	D	LASU
LA	Cocodrie	LUMC	2002/085	--------	30	sec	D	LASU
LA	English Turn	ENG1	1995/329	--------	30	sec	H	USCG
LA	English Turn	ENG2	--------	--------	30	sec	H	USCG
LA	Hammond	HAMM	2002/024	--------	30	sec	D	LASU
LA	Lafayette	KJUN	2002/024	--------	30	sec	D	LASU
LA	Winnfield	WNFL	1997/143	--------	30	sec	H	FSL
MA	Acushnet	ACU1	2002/067	--------	5	sec	H	USCG
MA	Acushnet	ACU2	2002/067	--------	5	sec	H	USCG
MA	Chatham	CHT1	1995/177	--------	30	sec	H	USCG
MA	Chatham	CHT2	--------	--------	30	sec	H	USCG
MA	Westford	WES2	1994/178	--------	30	sec	D	NGS
MD	Annapolis	ANP1	2001/171	--------	5	sec	H	USCG
MD	Annapolis	ANP2	--------	--------	5	sec	H	USCG
MD	Gaithersburg	GAIT	1994/110	--------	5	sec	H	NGS
MD	Gaithersburg	NIST	1994/040	1994/110	5	sec	H	NGS
MD	Greenbelt	GODE	1997/099	--------	30	sec	D	JPL
MD	Hagerstown	HAG1	2001/187	--------	5	sec	H	USCG
MD	Hagerstown	HAG2	2002/094	--------	5	sec	H	USCG
MD	Hagerstown	HTCC	2001/306	--------	5	sec	H	HCC
MD	Horn Point	HNPT	1999/319	--------	30	sec	D	NGS
MD	Solomons Island	SOL1	1999/319	--------	30	sec	D	NGS
ME	Bar Harbor	BARH	1998/275	--------	30	sec	D	NGS

ME	Brunswick	BRU1	1995/297	--------	30 sec	H	USCG
ME	Brunswick	BRU2	--------	--------	30 sec	H	USCG
ME	Eastport	EPRT	1998/275	--------	30 sec	D	NGS
ME	Orono	ORO_	1997/219	2000/124	5 sec	H	SATLOC
ME	Penobscot	PNB1	1999/099	--------	30 sec	H	USCG
ME	Penobscot	PNB2	--------	--------	30 sec	H	USCG
MI	Adrian	ADRI	2002/009	--------	1 sec	H	MDOT
MI	Alpena	NOR3	2001/243	--------	1 sec	H	MDOT
MI	Auburn Hills	METR	2001/243	--------	1 sec	H	MDOT
MI	Brighton	BRIG	2001/243	--------	1 sec	H	MDOT
MI	Cadillac	NOR1	2001/243	--------	1 sec	H	MDOT
MI	Cheboygan	CHB1	1995/226	--------	30 sec	H	USCG
MI	Cheboygan	CHB2	--------	--------	30 sec	H	USCG
MI	Detroit	DET1	1995/208	--------	30 sec	H	USCG
MI	Detroit	DET2	--------	--------	30 sec	H	USCG
MI	Escanaba	SUP2	2001/243	--------	1 sec	H	MDOT
MI	Gaylord	NOR2	2001/243	--------	1 sec	H	MDOT
MI	Grand Rapids	GRAR	2001/243	--------	1 sec	H	MDOT
MI	Jackson	UNIV	2001/243	--------	1 sec	H	MDOT
MI	Kalamazoo	SOWR	2001/243	--------	1 sec	H	MDOT
MI	L'Anse	SUP1	2001/243	--------	1 sec	H	MDOT
MI	Lansing	LANS	2002/102	--------	1 sec	H	MDOT
MI	Mt. Pleasant	MPLE	2002/009	--------	1 sec	H	MDOT
MI	Neebish Island	NEB3	1996/011	1999/250	30 sec	H	USCG
MI	Newberry	SUP3	2001/243	--------	1 sec	H	MDOT
MI	Pickford	PCK1	1999/252	--------	30 sec	H	USCG
MI	Pickford	PCK2	2002/120	--------	30 sec	H	USCG
MI	Saginaw	BAYR	2001/243	--------	1 sec	H	MDOT
MI	Saginaw Bay	SAG1	1995/236	--------	30 sec	H	USCG
MI	Saginaw Bay	SAG2	2002/120	--------	30 sec	H	USCG
MI	Upper Keweenaw	KEW1	1996/038	--------	30 sec	H	USCG
MI	Upper Keweenaw	KEW2	--------	--------	30 sec	H	USCG
MI	Whitefish Point	WHP1	1995/159	1999/267	30 sec	H	USCG
MI	Whitefish Point	WHP2	--------	--------	30 sec	H	USCG
MN	Pine River	PNR1	1995/047	--------	5 sec	H	USCG
MN	Pine River	PNR2	--------	--------	5 sec	H	USCG
MN	Wood Lake	WDLM	1999/278	--------	30 sec	H	FSL
MO	Bloomfield	BLMM	1999/178	--------	30 sec	H	FSL
MO	Conway	CNWM	1999/104	--------	30 sec	H	FSL
MO	Lathrop	LTHM	1999/106	--------	30 sec	H	FSL
MP	Capitol Hill	CNMI	2001/237	--------	5 sec	H	CNMI
MS	Okolona	OKOM	1999/323	--------	30 sec	H	FSL
MS	Stennis Space Cntr	NDBC	1996/297	--------	30 sec	H	FSL
MS	Vicksburg	VIC1	1995/158	--------	30 sec	H	USCG
MS	Vicksburg	VIC2	2002/120	--------	30 sec	H	USCG
MT	Billings	BIL1	2000/238	--------	5 sec	H	USCG
MT	Billings	BIL2	2000/238	--------	5 sec	H	USCG
MT	Polson	PLS1	2001/031	--------	5 sec	H	USCG
MT	Polson	PLS2	--------	--------	5 sec	H	USCG
NC	Asheville	ASHV	1997/185	--------	5 sec	H	NCGS
NC	Castle Hayne	CASL	2002/100	--------	5 sec	H	NCGS
NC	Conover	CONO	2001/273	--------	5 sec	H	NCGS
NC	Fayetteville	FAYR	2001/113	--------	5 sec	H	NCGS
NC	Fort Macon	FMC1	1995/199	2001/002	30 sec	H	USCG
NC	Fort Macon	FMC2	1995/205	2001/002	30 sec	H	USCG
NC	High Point	HIPT	1999/321	--------	5 sec	H	CofHP
NC	Hillsborough	HILB	2002/100	--------	5 sec	H	NCGS
NC	Kitty Hawk	DUCK	1997/300	--------	30 sec	H	NGS
NC	Lillington	LILL	2002/103	--------	5 sec	H	NCGS
NC	New Bern	NBR1	2000/356	2001/213	30 sec	H	USCG
NC	New Bern	NBR2	2000/356	--------	30 sec	H	USCG
NC	Raleigh	RALR	2001/082	--------	5 sec	H	NCGS
NC	Sanford	SNFD	2002/103	--------	5 sec	H	NCGS
NC	Washington	WASR	2001/082	--------	5 sec	H	NCGS

NC	Wilmington	WILR	2001/082	2001/353	5 sec	H	NCGS
ND	Bismark	BSMK	2002/006	--------	5 sec	H	NDDOT
NE	Fairbury	FBYN	1999/106	--------	30 sec	H	FSL
NE	McCook	RWDN	1999/106	--------	30 sec	H	FSL
NE	Merriman	MRRN	1999/028	--------	30 sec	H	FSL
NE	Neligh	NLGN	1999/231	--------	30 sec	H	FSL
NE	Whitney	WHN1	1998/303	--------	5 sec	H	USCG
NE	Whitney	WHN2	--------	--------	5 sec	H	USCG
NH	Bartlett	BARN	2001/038	--------	30 sec	H	FSL
NH	New Castle	POR2	1995/173	1999/118	30 sec	H	USCG
NH	New Castle	POR3	--------	--------	30 sec	H	USCG
NH	New Castle	POR4	1999/119	--------	30 sec	H	USCG
NJ	Newark	NJI2	2001/138	--------	1 sec	H	NJIT
NJ	Newark	NJIT	1998/292	2001/132	5 sec	H	NJIT
NJ	Sandy Hook	SHK1	1995/138	--------	5 sec	H	USCG
NJ	Sandy Hook	SHK2	2002/120	--------	5 sec	H	USCG
NM	Aztec	AZCN	1999/130	--------	30 sec	H	FSL
NM	Pie Town	PIE1	1994/355	--------	30 sec	D	JPL
NM	Tucumcari	TCUN	1997/344	--------	30 sec	H	FSL
NM	White Sands	WSMN	1995/118	--------	30 sec	H	FSL
NU	Esteli	ESTI	2000/145	--------	30 sec	D	NGS
NU	Managua	MANA	2000/145	--------	30 sec	D	NGS
NV	Currant	RAIL	2000/314	--------	30 sec	D	UNAVCO
NV	Denio	SHLD	2001/353	--------	30 sec	D	CWU
NV	Dyer	DYER	2000/314	--------	30 sec	D	UNAVCO
NV	Ely	EGAN	1999/169	--------	30 sec	D	HSCfA
NV	Empire	GARL	2000/314	--------	30 sec	D	UNAVCO
NV	Fallon	UPSA	2000/314	--------	30 sec	D	UNAVCO
NV	Gabbs	GABB	2000/314	--------	30 sec	D	UNAVCO
NV	Las Vegas	LVWD	2001/001	--------	1 sec	H	LVVWD
NV	Oreana	TUNG	1999/169	--------	30 sec	D	HSCfA
NV	near Pioche	ECHO	2000/314	--------	30 sec	D	UNAVCO
NY	East Moriches	MOR1	1998/281	--------	30 sec	H	USCG
NY	East Moriches	MOR2	2002/120	--------	30 sec	H	USCG
NY	Hudson Falls	HDF1	2000/321	--------	30 sec	H	USCG
NY	Hudson Falls	HDF2	--------	--------	30 sec	H	USCG
NY	Montauk Point	MNP1	1995/138	1998/276	30 sec	H	USCG
NY	Palisades	LAMT	2001/231	--------	30 sec	H	LAMT
NY	Paul Smiths	PSC1	2001/075	-------	5 sec	H	PSC
NY	Syracuse	SYCN	1999/278	--------	30 sec	H	FSL
NY	Youngstown	YOU1	1996/100	--------	30 sec	H	USCG
NY	Youngstown	YOU2	2002/120	--------	30 sec	H	USCG
OH	Athens	STKR	2000/059	--------	5 sec	H	AEC
OH	Cincinnati	GALB	1998/005	--------	5 sec	H	CofC
OH	Columbus	COLB	2001/351	--------	5 sec	H	OHDOT
OH	Defiance	DEFI	2001/348	--------	5 sec	H	OHDOT
OH	Freeport	FREO	2001/348	--------	5 sec	H	OHDOT
OH	Gustavus	GUST	2001/351	--------	5 sec	H	OHDOT
OH	Lebanon	LEBA	2001/348	--------	5 sec	H	OHDOT
OH	McConnelsville	MCON	2001/352	--------	5 sec	H	OHDOT
OH	Piketon	PKTN	2001/354	--------	5 sec	H	OHDOT
OH	Sidney	SIDN	2001/348	--------	5 sec	H	OHDOT
OH	Tiffin	TIFF	2001/348	--------	5 sec	H	OHDOT
OH	Wooster	WOOS	2001/348	--------	5 sec	H	OHDOT
OK	Lamont	LMNO	1995/023	--------	30 sec	H	FSL
OK	Morris	HKLO	1995/115	--------	30 sec	H	FSL
OK	Purcell	PRCO	1995/334	--------	30 sec	H	FSL
OK	Sallisaw	SAL1	1996/228	--------	30 sec	H	USCG
OK	Sallisaw	SAL2	2002/120	--------	30 sec	H	USCG
OK	Vici	VCIO	1995/113	--------	30 sec	H	FSL
OR	Burns Junction	BURN	1999/081	--------	30 sec	D	UWA
OR	Corvallis	CORV	1998/186	--------	30 sec	D	OSU
OR	Fort Stevens	FTS1	1996/019	--------	30 sec	H	USCG
OR	Fort Stevens	FTS2	--------	--------	30 sec	H	USCG

OR	Newport	NEWP	1998/186	--------	30 sec	D	OSU
OR	Port Orford	CABL	1998/057	--------	30 sec	D	CWU
OR	Redman	REDM	1998/210	--------	30 sec	D	CWU
OR	Roseburg	DDSN	2001/353	--------	30 sec	D	PANGA
OR	Tillamook	CHZZ	2001/353	--------	30 sec	D	CWU
PA	Hawk Run	HRN1	2001/268	--------	5 sec	H	USCG
PA	Hawk Run	HRN2	2001/268	2002/092	5 sec	H	USCG
PA	Lehman	WIL1	1997/083	--------	5 sec	H	PADOT
PA	Pittsburgh	PIT1	1997/048	--------	5 sec	H	PADOT
PA	State College	PSU1	1997/289	--------	5 sec	H	PADOT
PA	Titusville	UPTC	2000/292	--------	5 sec	H	PADOT
PR	Isabela	PUR1	1996/345	1997/052	30 sec	H	USCG
PR	Isabela	PUR2	1997/041	2001/024	30 sec	H	USCG
PR	Isabela	PUR3	1997/052	--------	30 sec	H	USCG
RI	Newport	NPRI	1999/319	--------	30 sec	D	NGS
SC	Charleston	CHA1	1995/241	--------	30 sec	H	USCG
SC	Charleston	CHA2	1995/241	2001/305	30 sec	H	USCG
SC	Columbia	COLA	1998/243	--------	5 sec	H	SCGS
SC	Darlington	FDTC	2001/225	--------	15 sec	H	SCGS
SC	Greenville	GVLT	2001/171	--------	5 sec	H	GTI
SD	Clark	CLK1	1999/197	--------	30 sec	H	USCG
SD	Clark	CLK2	--------	--------	30 sec	H	USCG
TN	Hartville	HTV1	1999/179	--------	30 sec	H	USCG
TN	Hartville	HTV2	2002/120	--------	30 sec	H	USCG
TX	Amarillo	AML5	1996/016	--------	5 sec	D	TXDOT
TX	Aransas Pass	ARP1	1995/263	1995/312	30 sec	H	USCG
TX	Aransas Pass	ARP2	--------	--------	30 sec	H	USCG
TX	Aransas Pass	ARP3	1995/335	--------	30 sec	H	USCG
TX	Arlington	ARL5	1996/018	--------	5 sec	D	TXDOT
TX	Austin	AUS5	1996/017	--------	5 sec	D	TXDOT
TX	Beaumont	BEA5	1996/022	--------	5 sec	d	TXDOT
TX	Corpus Christi	CORC	1996/018	--------	5 sec	D	TXDOT
TX	EL Paso	ELP3	2001/025	--------	5 sec	D	TXDOT
TX	El Paso	PASO	1996/021	2000/341	5 sec	D	TXDOT
TX	Fort Davis	MDO1	1995/267	--------	30 sec	D	JPL
TX	Galveston	GAL1	1995/272	--------	30 sec	H	USCG
TX	Galveston	GAL2	2001/291	--------	30 sec	H	USCG
TX	Houston	ADKS	2002/051	--------	30 sec	D	HGCSD
TX	Houston	HOUS	1996/018	--------	5 sec	D	TXDOT
TX	Houston	LKHU	1995/250	--------	30 sec	D	HGCSD
TX	Houston	NETP	2002/050	--------	30 sec	D	HGCSD
TX	Jayton	JTNT	1997/142	--------	30 sec	H	FSL
TX	Laredo	LARD	2002/028	--------	5 sec	D	TXDOT
TX	Lubbock	LUBB	1996/018	--------	5 sec	D	TXDOT
TX	Odessa	ODS5	1996/021	--------	5 sec	D	TXDOT
TX	Palestine	PATT	1997/143	--------	30 sec	H	FSL
TX	Pharr	PHAR	2002/028	--------	5 sec	D	TXDOT
TX	San Antonio	ANTO	1996/018	--------	5 sec	D	TXDOT
TX	Summerfield	SUM1	2001/024	--------	30 sec	H	USCG
TX	Summerfield	SUM2	--------	--------	30 sec	H	USCG
UT	Myton	MYT1	2002/067	--------	5 sec	H	USCG
UT	Myton	MYT2	2002/067	2002/148	30 sec	H	USCG
UT	Price	PUC1	2001/063	--------	5 sec	H	CCO
UT	Salt Lake City	RBUT	1997/102	--------	30 sec	H	UNAVCO
UT	Salt Lake City	SLCU	2001/301	--------	30 sec	H	FSL
UT	Salt Lake City	SUR1	1997/102	1998/220	30 sec	H	UNAVCO
VA	Blacksburg	BLKV	1999/201	--------	30 sec	H	FSL
VA	Cape Henry	CHR1	1995/342	1999/169	30 sec	H	USCG
VA	Chesapeake Light	COVX	2002/011	--------	5 sec	H	FSL
VA	Corbin	CORB	2001/048	--------	5 sec	H	NGS
VA	Driver	DRV1	1999/197	--------	30 sec	H	USCG
VA	Driver	DRV2	2001/291	--------	30 sec	H	USCG
VA	Fan Mountain	UVFM	2001/228	--------	30 sec	H	UVA
VA	Gloucester Point	GLPT	1999/319	--------	30 sec	D	NGS

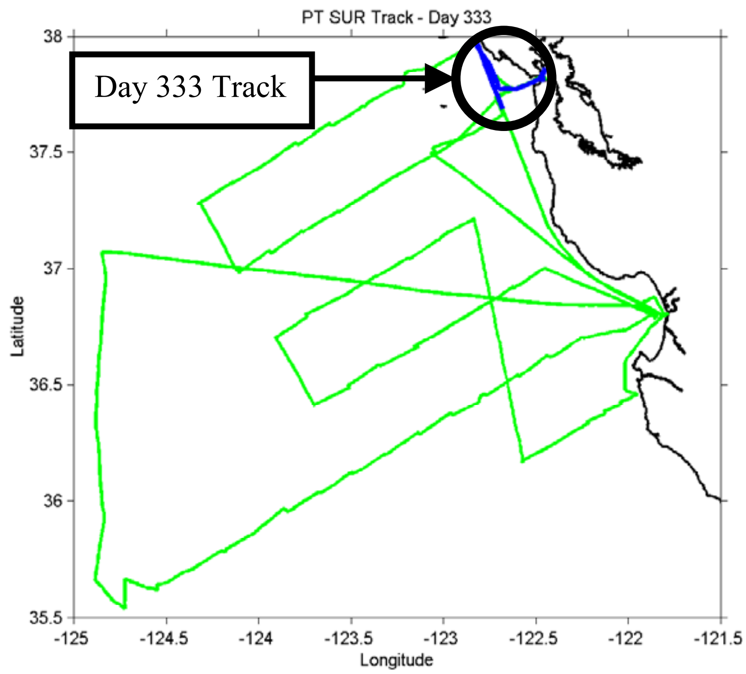
VA	Richmond	RIC1	1997/105	--------	5 sec	H	VDOT
VA	Wachapreague	VIMS	1999/319	--------	30 sec	D	NGS
VQ	Christiansted	CRO1	1996/231	--------	30 sec	D	JPL
VT	Montpelier	VCAP	1996/158	--------	5 sec	H	VAOT
WA	Appleton	GWEN	1997/135	--------	30 sec	H	USCG
WA	Appleton	GWN2	2001/291	2002/092	30 sec	H	USCG
WA	Ellensburg	LIND	1998/210	--------	30 sec	D	CWU
WA	Ellensburg	SC00	2001/353	--------	30 sec	D	UNAVCO
WA	Golendale	GOBS	1998/057	--------	30 sec	D	CWU
WA	Kelso	KELS	1999/081	--------	30 sec	D	UWA
WA	La Grande	CPXF	2001/353	--------	30 sec	D	CWU
WA	Neah Bay	NEAH	1998/058	--------	30 sec	D	UWA
WA	Pacific Beach	PABH	1998/057	--------	30 sec	D	CWU
WA	Robinson Point	RPT1	1995/271	--------	30 sec	H	USCG
WA	Robinson Point	RPT2	2002/120	--------	30 sec	H	USCG
WA	Seattle	SEAT	1998/058	--------	30 sec	D	UWA
WA	Seattle	SEAW	1999/027	--------	30 sec	H	FSL
WA	Sedro Wooley	SEDR	1998/057	--------	30 sec	D	UWA
WA	Spokane	SPN1	2001/030	--------	30 sec	H	USCG
WA	Spokane	SPN2	--------	--------	30 sec	H	USCG
WA	Tumwater	TWHL	2001/355	--------	30 sec	D	CWU
WA	Whidbey Island	WHD1	1995/351	--------	30 sec	H	USCG
WA	Whidbey Island	WHD2	2002/120	--------	30 sec	H	USCG
WI	Alma	STP1	1996/228	--------	30 sec	H	USCG
WI	Alma	STP2	2002/120	--------	30 sec	H	USCG
WI	Blue River	BLRW	1999/278	--------	30 sec	H	FSL
WI	Milwaukee	MIL1	1995/276	--------	30 sec	H	USCG
WI	Milwaukee	MIL2	2002/120	--------	30 sec	H	USCG
WI	Sturgeon Bay	STB1	1996/019	--------	30 sec	H	USCG
WI	Sturgeon Bay	STB2	2002/120	--------	30 sec	H	USCG
WI	Wisconsin Point	WIS1	1996/100	--------	30 sec	H	USCG
WI	Wisconsin Point	WIS2	2002/120	--------	30 sec	H	USCG
WY	Boulder	BLWY	2000/133	--------	30 sec	D	UNAVCO
WY	Casper	CASP	2000/123	--------	30 sec	D	NGS
WY	Mammoth	MAWY	2000/133	--------	30 sec	D	UNAVCO
WY	Medicine Bow	MBWW	1999/033	--------	30 sec	H	FSL

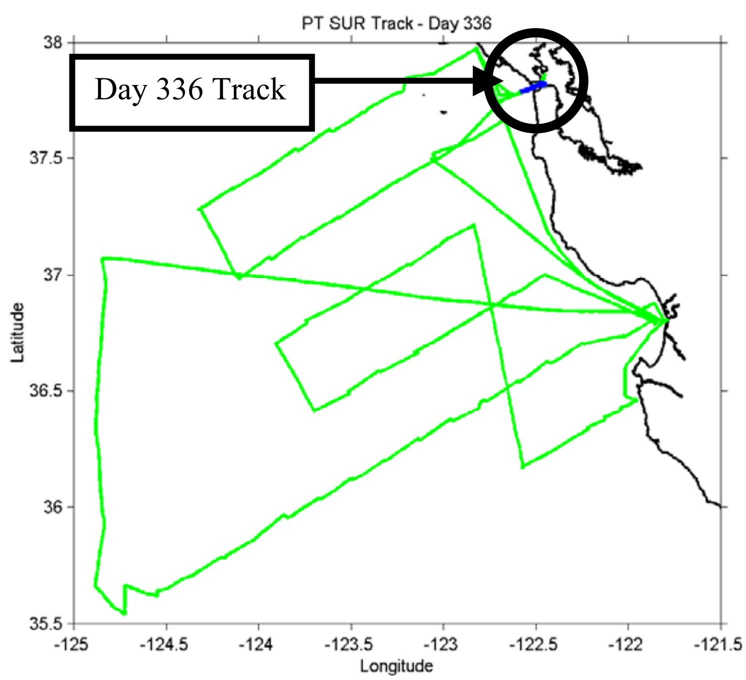
	Organization
AEC	Ohio University Avionics Engineering Center
ASDC	American Samoa Department of Commerce
BAYONET	Bayonet Network
BLM	Bureau of Land Management (NOAA)
CCO	Carbon County, UT
CETI	Condor Earth Technologies Inc
CNMI	Commonwealth of the Northern Marianas Islands, TQ
CofC	City of Cincinnati, OH
CofHP	City of High Point, NC
CofS	City of Scottsdale, AZ
CofT	City of Tucson, AZ
CWU	Central Washington University (PANGA)
DEDP	Delaware Department of Parks and Recreation
FSL	Forecast System Laboratory (NOAA)
GTI	Greenville Technical Institute
HCC	Hagerstown Community College, MD
HGCSD	Harris Galveston Coastal Subsidence District
HSCfA	Harvard-Smithsonian Center for Astrophysics (BARGN)
IDDOT	Idaho Department of Transportation
IGN	Instituto Geografico Nacional (NOAA)
INETER	Instituto Nicaraguense de Estudios Territoriales (NOAA)
INUN	Indiana University, IN
JAMET	Jamaica Meterological Service (NOAA)
JPL	Jet Propulsion Laboratory
LAMT	Lamont Earth Observatory, NY
LCDT	Lake County Division of Transportation

LLNL	Lawrence Livermore National Laboratory, CA
LVVWD	Las Vegas Valley Water District
MDOT	Michigan Department of Transportation
NCAD	NCAD Corporation, KY
NCGS	North Carolina Geodetic Survey
NDDOT	North Dakota Dept. of Transportation
NGS	National Geodetic Survey (NOAA)
NJIT	New Jersey Institute of Technology
ODOT	Ohio Department of Transportation
OSU	Oregon State University (PANGA)
PADOT	Pennsylvania Department of Transportation
PGPS	Pacific GPS Facility
PSC	Paul Smith's College
SRP	Salt River Project, AZ
SATLOC	SATLOC Inc
SCGS	South Carolina Geodetic Survey
SOPAC	Scripps Orbit and Permanent Array Center (SCIGN)
SOPAC	Scripps Orbit and Permanent Array Center (RIVCOFLOOD)
SPSU	Southeastern Polytechnic University, GA
TRS	Columbia County, GA
TSEA	The Surveyors Exchange, AK
TXDOT	Texas Department of Transportation
UCB	University of California, Berkeley (BARD)
UNAVCO	University of Utah
USACE	US Army Corps of Engineers
USCG	US Coast Guard
USDOT	US Department of Transportation (USCG)
USGS	US Geological Survey (BARD)
USGS	US Geological Survey (SCIGN)
USNO	US Naval Observatory (JPL)
UVA	University of Virginia
UWA	University of Washington (PANGA)
VAOT	Vermont Agency of Transportation
VDOT	Virginia Department of Transportation

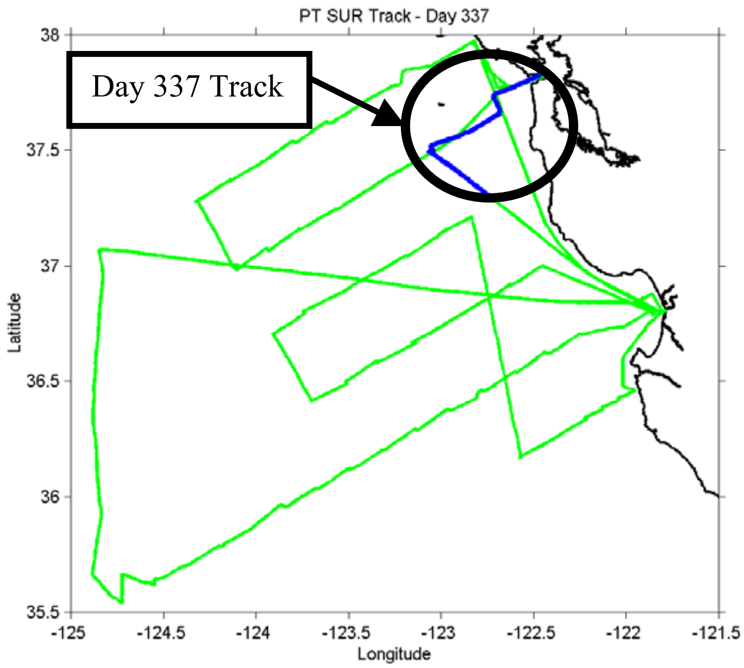
APPENDIX B: DAY TRACKS FOR PT SUR EXPERIMENT

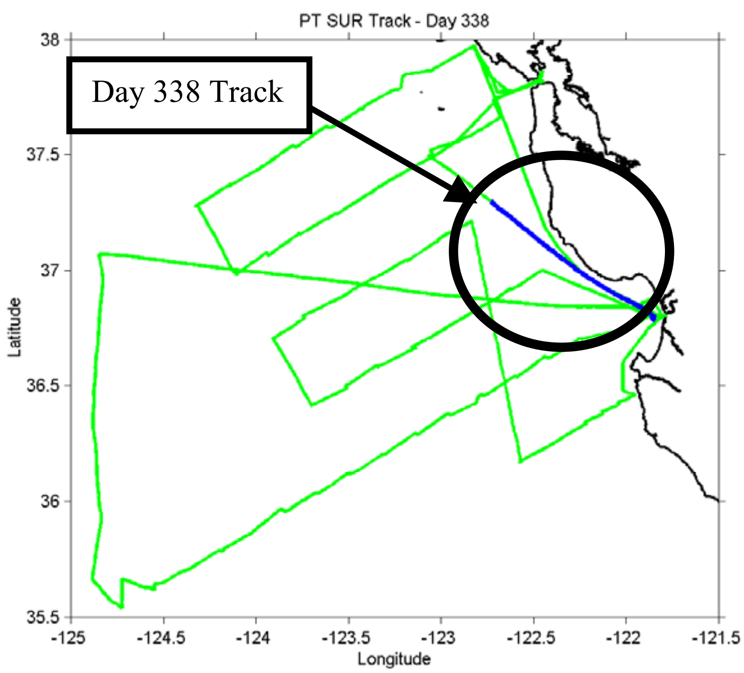
The following plots show the ship's track for the entire experiment, the light colored track, and each day's track, highlighted in bold. Days 333 and 336 were spent in and around San Francisco Bay. Oceanographic surveys were performed on Day 336 near the Golden Gate Bridge.





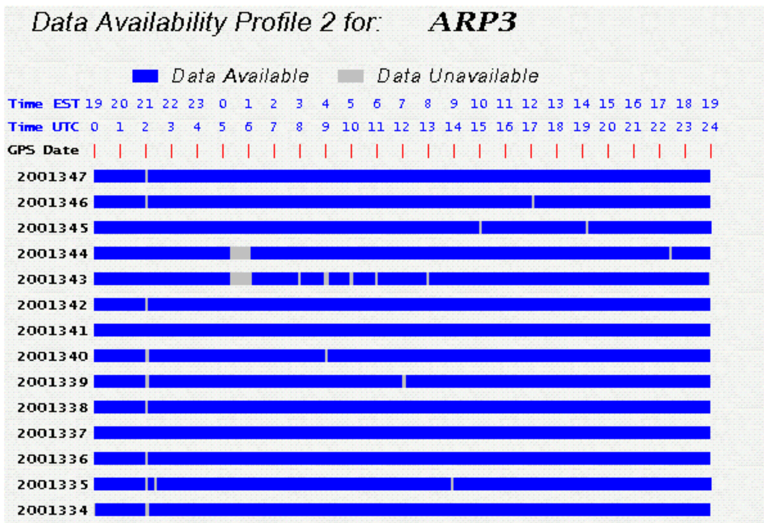
Open ocean transits were conducted on Days 337 and 338.

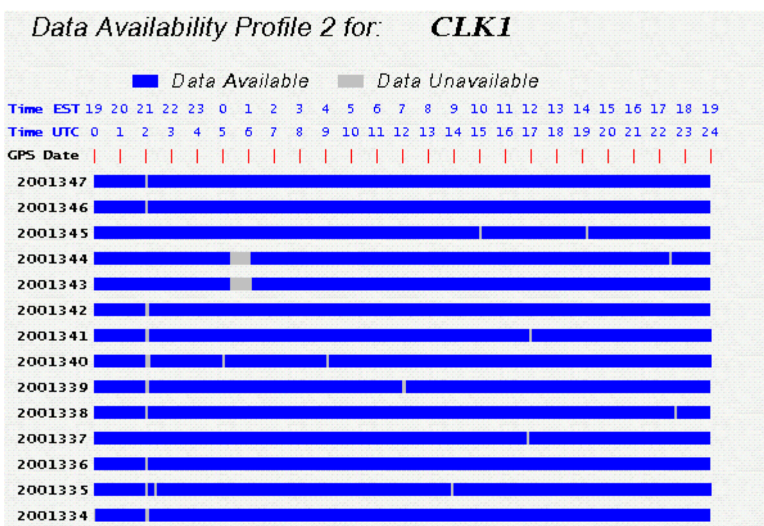


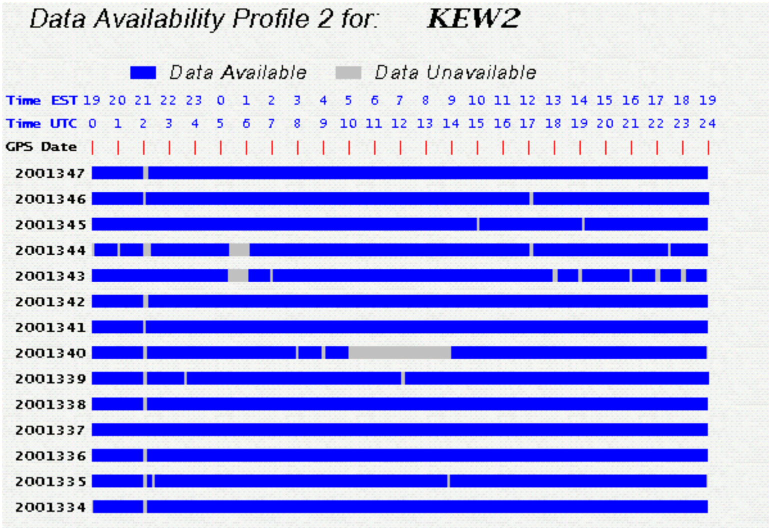


APPENDIX C: REFERENCE STATION DATA AVAILABILITY

The following graphs, available from CORS, display the times of day when that reference station collected data and made it publicly available. There are gaps in the datasets at 0200 UTC on most days. These gaps in the raw data reflected as gaps in the solutions.



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Data Available
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Time UTC 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
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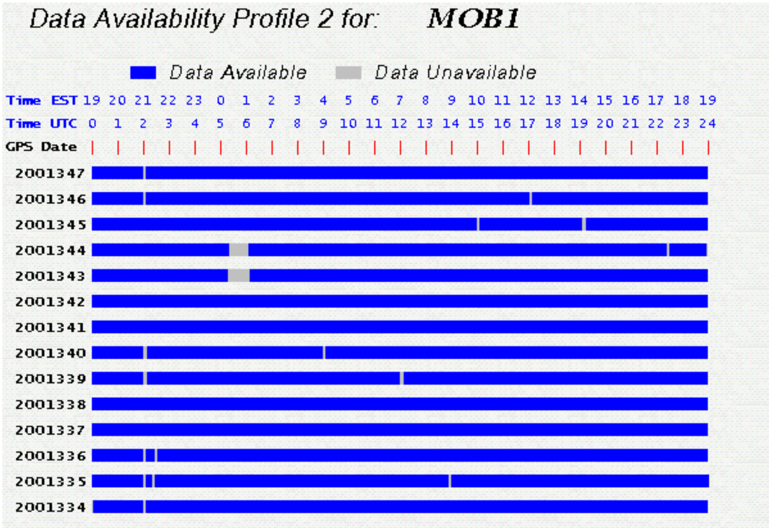
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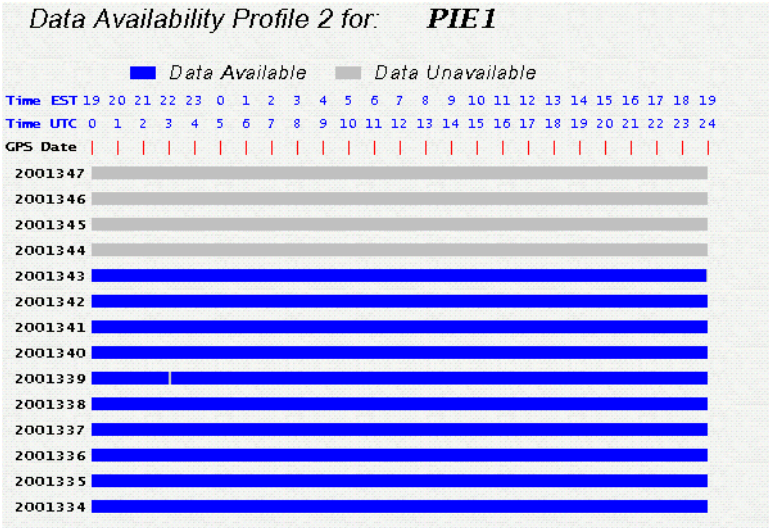
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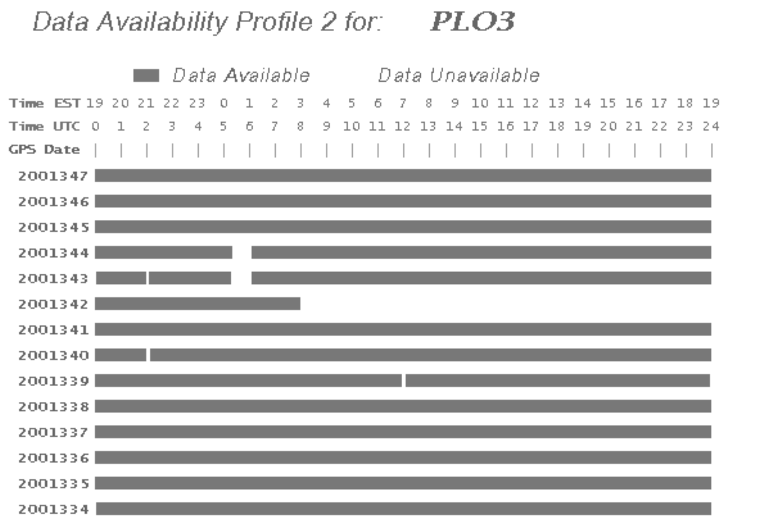
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Data Unavailable
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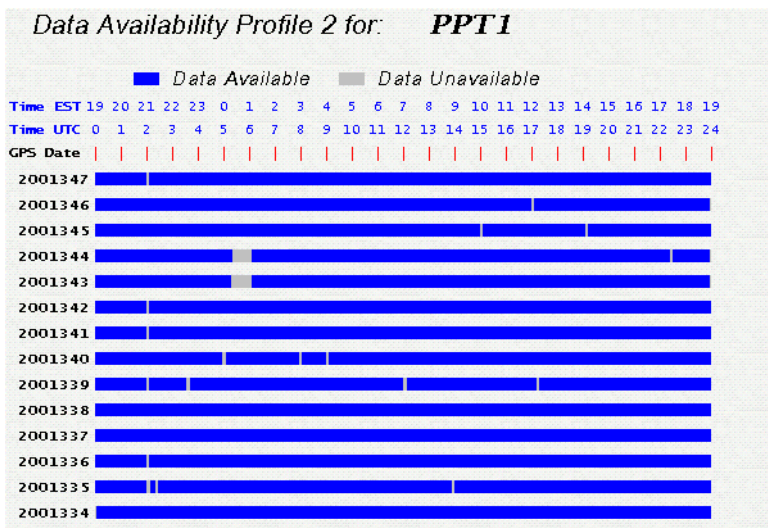
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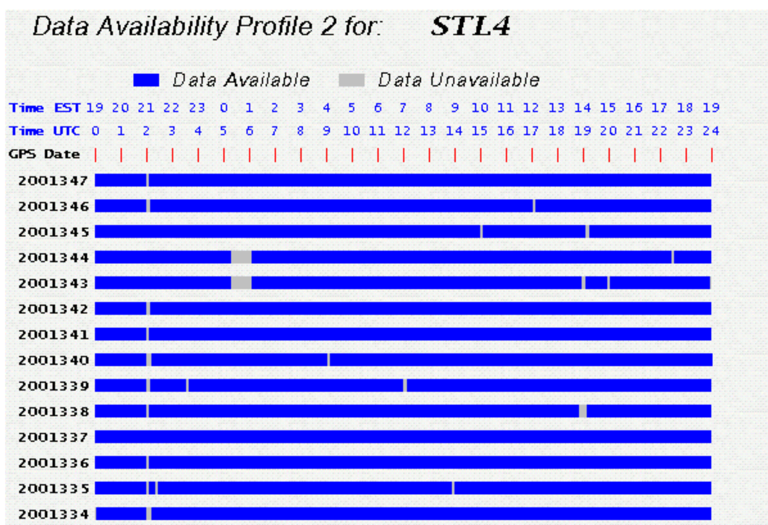
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APPENDIX D: DAY-BY-DAY NO TROPOSPHERE EFFECT MODEL AND TROPOSPHERE EFFECT MODEL MEAN VALUES

The following tables provide the day-by-day mean values for the number of satellites used to compute the solution, the mean delta (North, East, Up), the mean delta residual sum of squares of the horizontal position (RSS), and the improvement over the baseline case in (North, East, Up, RSS).

Table 7. No Troposphere Effect Model – Mean Values

						Mean					
Site	**Day**	**Range**	**# Satellites**	μ_{North}	μ_{East}	μ_{Up}	μ_{RSS}	**Improve N**	**Improve E**	**Improve U**	**Improve R**
ARP	333	2500	7.37	-0.60	-0.02	-1.47	0.60	1.89	0.96	2.84	2.06
ARP	336	2500	7.75	-0.86	0.04	-1.15	0.87	1.19	0.38	2.22	1.12
ARP	337	2500	7.68	-0.75	0.11	-0.82	0.75	1.64	0.63	1.89	1.67
ARP	338	2500	7.65	-0.44	-0.09	-1.29	0.45	1.75	0.66	2.93	1.79
CLK	333	2200	7.28	-0.55	-0.51	-0.64	0.75	3.04	2.62	5.71	4.20
CLK	336	2200	7.64	-0.63	-0.62	-0.75	0.89	2.44	2.08	5.46	3.36
CLK	337	2200	7.61	-0.61	-0.54	-0.58	0.81	2.86	2.31	4.86	3.87
CLK	338	2200	7.54	-0.30	-0.54	-0.62	0.62	2.85	2.24	6.06	3.83
KEW	333	3000	7.29	-0.42	0.05	-0.71	0.43	2.10	1.47	3.89	2.58
KEW	336	3000	7.65	-0.61	-0.29	-1.16	0.67	1.68	1.26	3.72	2.13
KEW	337	3000	7.59	-0.44	-0.14	-1.01	0.46	2.05	1.39	2.92	2.52
KEW	338	3000	7.55	-0.25	-0.24	-1.02	0.35	1.85	1.33	4.09	2.31
MOB	333	3200	7.41	-0.45	-0.05	-1.68	0.45	2.32	1.08	3.96	2.50
MOB	336	3200	7.75	-0.60	-0.40	-1.96	0.72	1.85	0.81	3.44	1.93
MOB	337	3200	7.75	-0.54	-0.30	-1.64	0.62	2.21	0.91	3.24	2.30
MOB	338	3200	7.71	-0.23	-0.47	-2.24	0.52	2.26	0.80	4.19	2.29
PIE	333	1300	7.28	0.04	-0.20	-3.25	0.20	3.41	2.13	5.87	4.14
PIE	336	1300	7.53	0.14	-0.33	-3.23	0.36	2.97	1.79	5.40	3.58
PIE	337	1300	7.59	0.03	-0.25	-2.69	0.26	2.88	1.67	5.19	3.42
PIE	338	1300	7.40	0.30	-0.25	-2.71	0.39	3.12	1.65	6.65	3.60
PLO	333	600	7.27	-0.55	-0.36	-0.04	0.65	3.16	2.62	5.71	4.30
PLO	336	600	7.62	-0.50	-0.48	0.08	0.69	2.59	2.16	5.57	3.53
PLO	337	600	7.59	-0.49	-0.30	1.59	0.58	3.15	2.48	5.61	3.91
PLO	338	600	7.49	-0.28	-0.44	-0.04	0.52	3.05	2.34	6.27	4.05
PPT	333	100	7.25	-0.33	-0.48	-0.11	0.58	3.26	2.64	5.99	4.41
PPT	336	100	7.63	-0.39	-0.64	0.15	0.75	2.67	2.15	5.64	3.61
PPT	337	100	7.59	-0.47	-0.64	-0.09	0.79	3.08	2.33	5.02	4.06
PPT	338	100	7.49	-0.25	-0.53	-0.11	0.59	3.10	2.41	6.52	4.14
STL	333	2800	7.30	-0.38	-0.20	-1.09	0.43	2.85	2.09	5.35	3.66
STL	336	2800	7.64	-0.52	-0.36	-1.51	0.63	2.26	1.50	4.66	2.78
STL	337	2800	7.62	-0.47	-0.19	-1.04	0.51	2.58	1.70	4.00	3.19
STL	338	2800	7.55	-0.23	-0.24	-1.49	0.33	2.59	1.67	5.32	3.18

Table 8. Troposphere Model – Mean Values

						Mean					
Site	Day	Range	# Satellites	μ_{North}	μ_{East}	μ_{Up}	μ_{RSS}	Improve N	Improve E	Improve U	Improve R
ARP	333	2500	7.37	-1.80	3.65	-1.47	4.07	1.26	-1.30	5.27	-0.07
ARP	336	2500	7.75	-1.89	3.57	-1.15	4.04	0.52	-1.74	6.10	-0.95
ARP	337	2500	7.68	-1.82	3.83	-0.82	4.24	1.06	-1.67	5.47	-0.48
ARP	338	2500	7.65	-1.51	3.56	-1.29	3.86	1.08	-1.53	5.70	-0.37
CLK	333	2200	7.28	0.72	2.41	-0.64	2.51	3.19	0.56	7.83	2.71
CLK	336	2200	7.64	0.75	2.39	-0.75	2.50	2.54	0.20	8.50	1.94
CLK	337	2200	7.61	0.76	2.44	-0.58	2.55	3.03	0.37	7.72	2.46
CLK	338	2200	7.54	1.28	2.40	-0.62	2.72	2.57	0.29	8.85	2.15
KEW	333	3000	7.29	1.43	3.49	-0.71	3.77	1.94	-0.80	6.21	0.69
KEW	336	3000	7.65	1.34	3.23	-1.16	3.49	1.41	-0.86	6.99	0.25
KEW	337	3000	7.59	1.52	3.17	-1.01	3.51	1.82	-0.70	5.79	0.68
KEW	338	3000	7.55	1.89	3.13	-1.02	3.65	1.26	-0.78	6.93	0.25
MOB	333	3200	7.41	-0.69	4.07	-1.68	4.13	2.08	-1.96	5.39	-0.18
MOB	336	3200	7.75	-0.81	3.66	-1.96	3.75	1.51	-1.99	6.16	-0.57
MOB	337	3200	7.75	-0.66	3.73	-1.64	3.79	1.93	-1.86	5.70	-0.15
MOB	338	3200	7.71	-0.29	3.64	-2.24	3.65	1.92	-2.02	6.25	-0.32
PIE	333	1300	7.28	-0.27	1.18	-3.25	1.21	3.32	1.26	6.89	3.46
PIE	336	1300	7.53	-0.17	0.99	-3.23	1.01	2.76	1.00	7.28	2.83
PIE	337	1300	7.59	-0.35	1.28	-2.69	1.33	2.76	0.88	6.88	2.77
PIE	338	1300	7.40	0.09	1.14	-2.71	1.14	3.01	0.88	7.90	2.91
PLO	333	600	7.27	-1.57	0.58	-0.04	1.68	2.49	2.25	8.66	3.53
PLO	336	600	7.62	-1.58	0.51	0.08	1.66	1.81	1.89	9.43	2.74
PLO	337	600	7.59	-1.18	0.44	1.59	1.26	2.54	2.11	9.17	3.46
PLO	338	600	7.49	-1.15	0.44	-0.04	1.23	2.53	2.12	9.56	3.50
PPT	333	100	7.25	-0.48	-0.45	-0.11	0.66	3.30	2.61	9.19	4.45
PPT	336	100	7.63	-0.55	-0.63	0.15	0.84	2.59	2.15	9.72	3.55
PPT	337	100	7.59	-0.60	-0.61	-0.09	0.86	3.08	2.32	8.71	4.07
PPT	338	100	7.49	-0.15	-0.62	-0.11	0.64	3.15	2.38	10.09	4.18
STL	333	2800	7.30	0.30	3.65	-1.09	3.66	2.58	-0.90	6.57	1.00
STL	336	2800	7.64	0.20	3.42	-1.51	3.43	2.07	-1.18	7.11	0.39
STL	337	2800	7.62	0.25	3.70	-1.04	3.71	2.42	-1.09	6.37	0.75
STL	338	2800	7.55	0.64	3.61	-1.49	3.67	2.23	-1.24	7.26	0.49

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